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Module 3

Stormwater Engineering Concepts

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Module 3 Content

3.a Why stormwater engineering concepts?

3.b Hydrologic Cycle

3.c Quantity

3c1. Rainfall–Runoff Relationships

- **Hydrographs**
- **Stream flow-gauged watersheds**
- **Hydrograph Development (Synthetic – ungauged)**
- **Rv, C value, CN**

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3.c Quantity (cont.)

3c2. Rational Method

3c3. Modified Rational Method

3c4. TR-55

3c5. TR-55 – Storage Volume

3c6. Control Structures

3.d Quality

3d1. Simple Method

3d2. Treatment volume

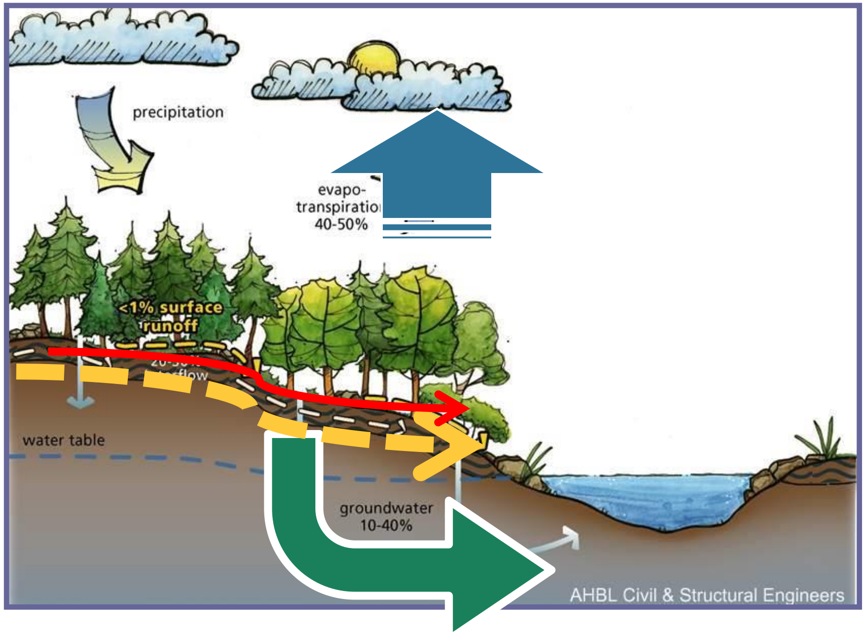
3.e Conversion of volume to flow

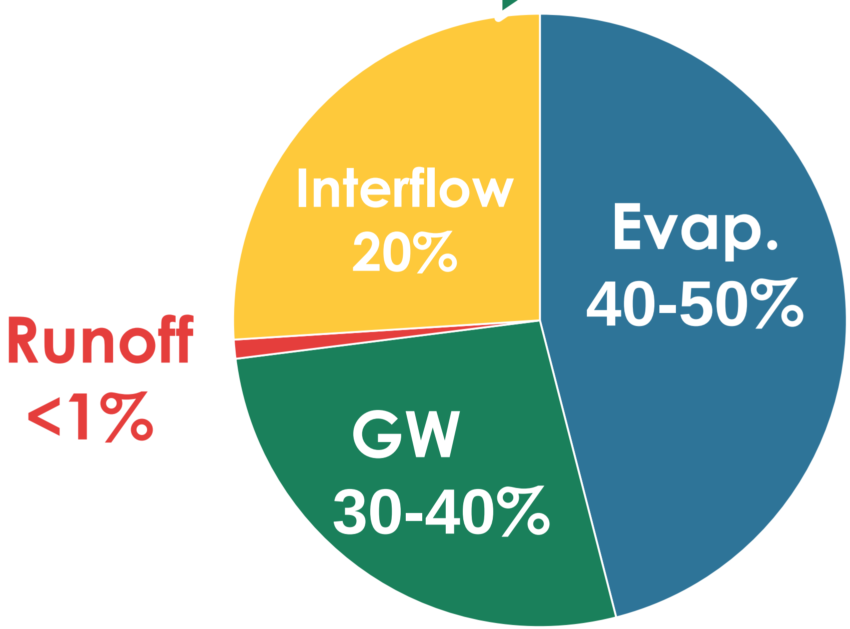
Why stormwater engineering concepts?

Roadmap to Water Quantity & Quality

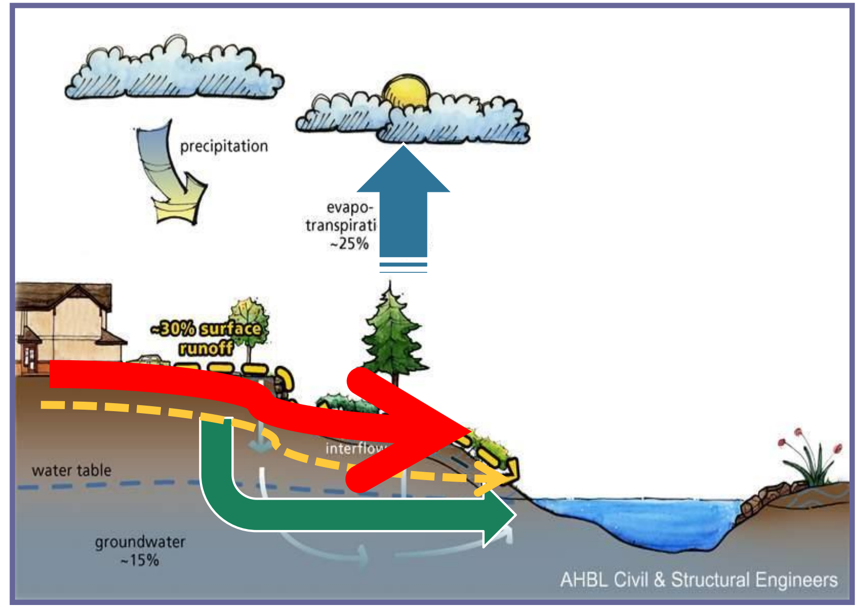
Natural Resources	Water Quantity	Water Quality
• Land Cover • Soils • Optimize Site Design • Mimic (ESD)	• Channel/Flood Protection *(9VAC25-870-66)* • Discharge • Volume • Duration	• Runoff Reduction Method *(9VAC25-870-63)* • Concentration • Volume • Load (mg/L * ft^3)

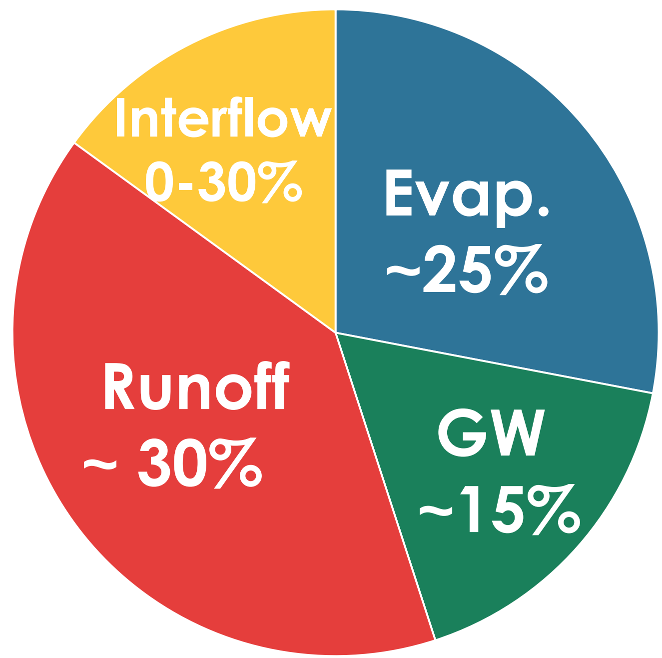
Pre-Developed Hydrology

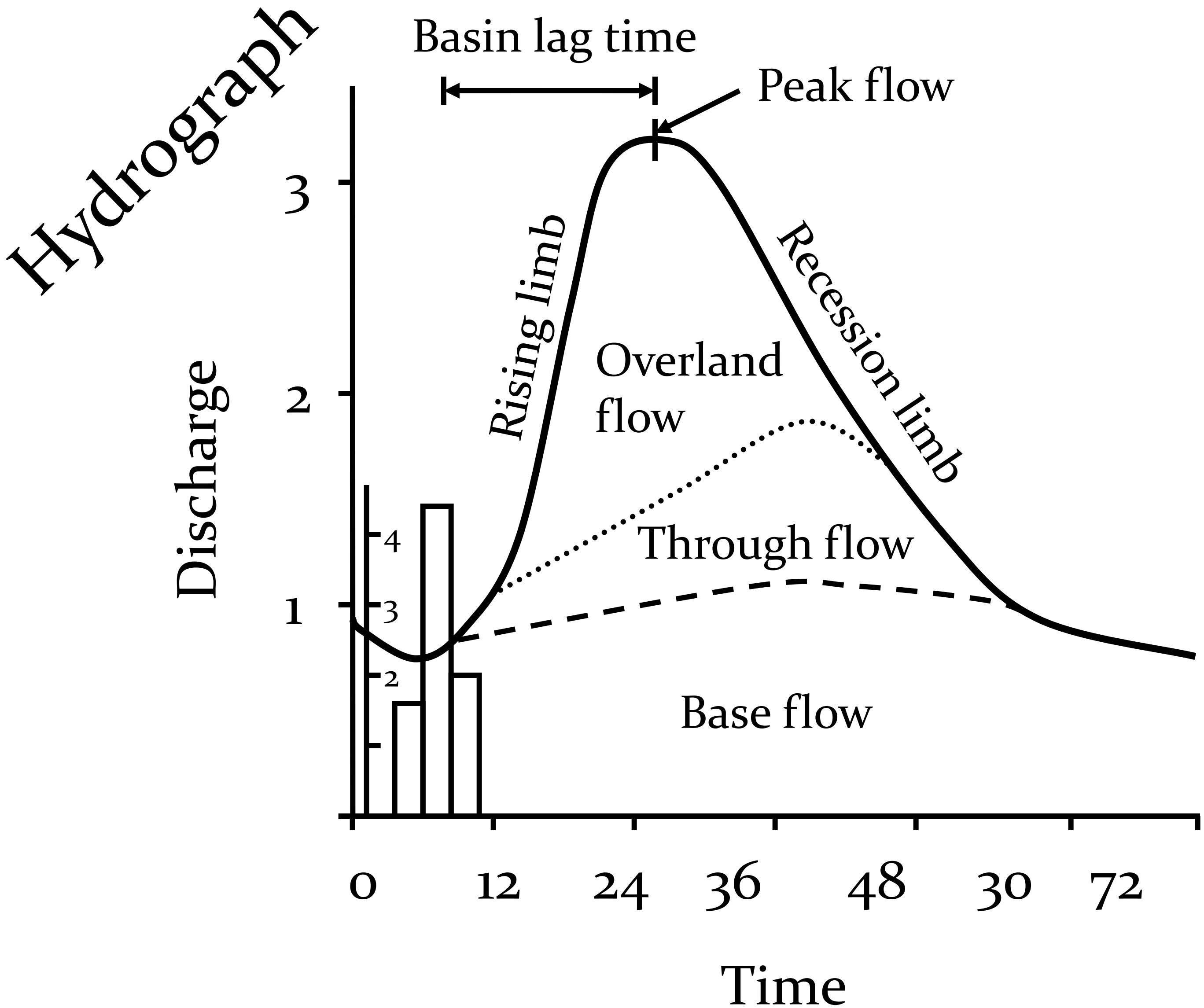




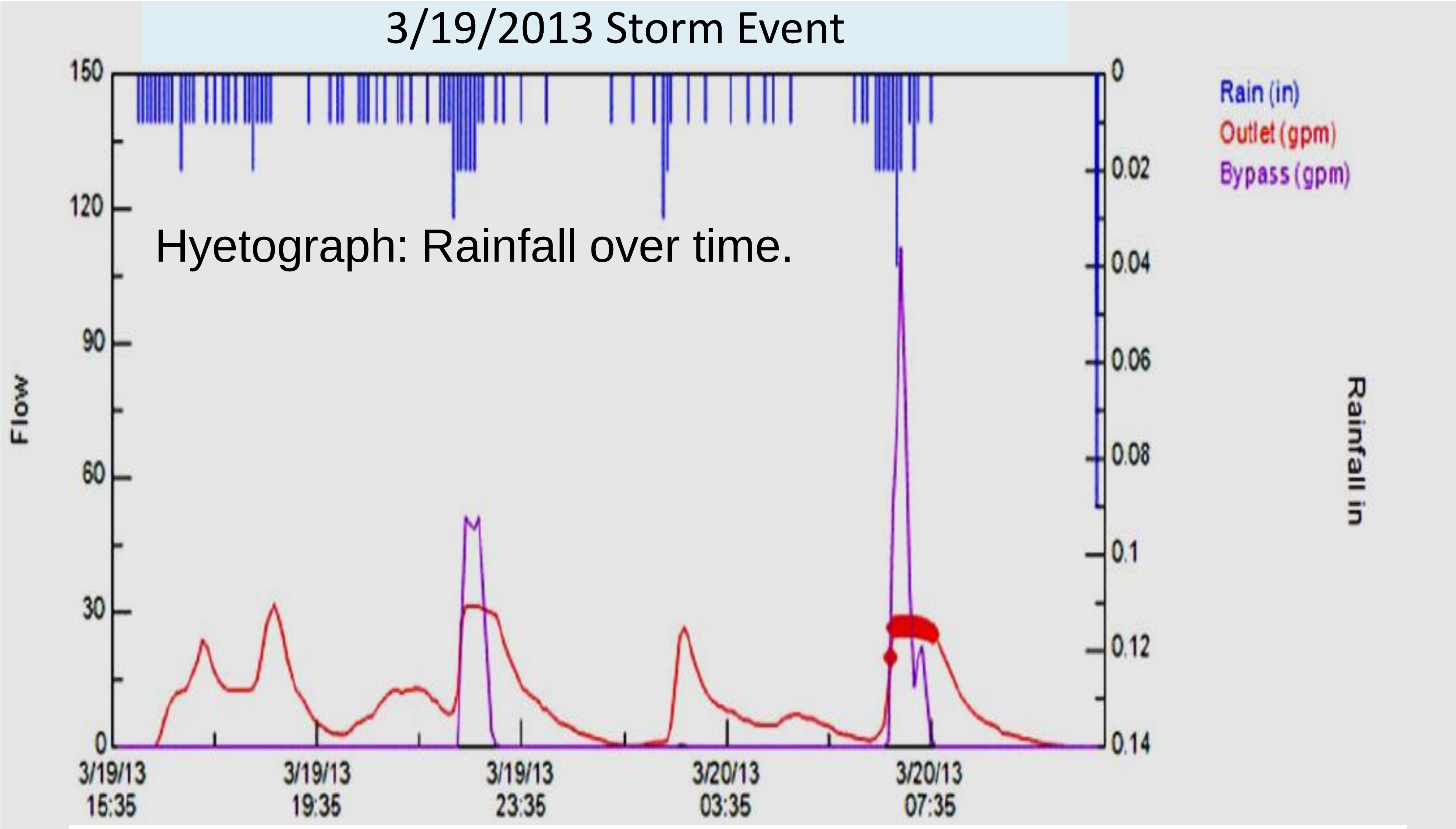
Post-Developed Hydrology





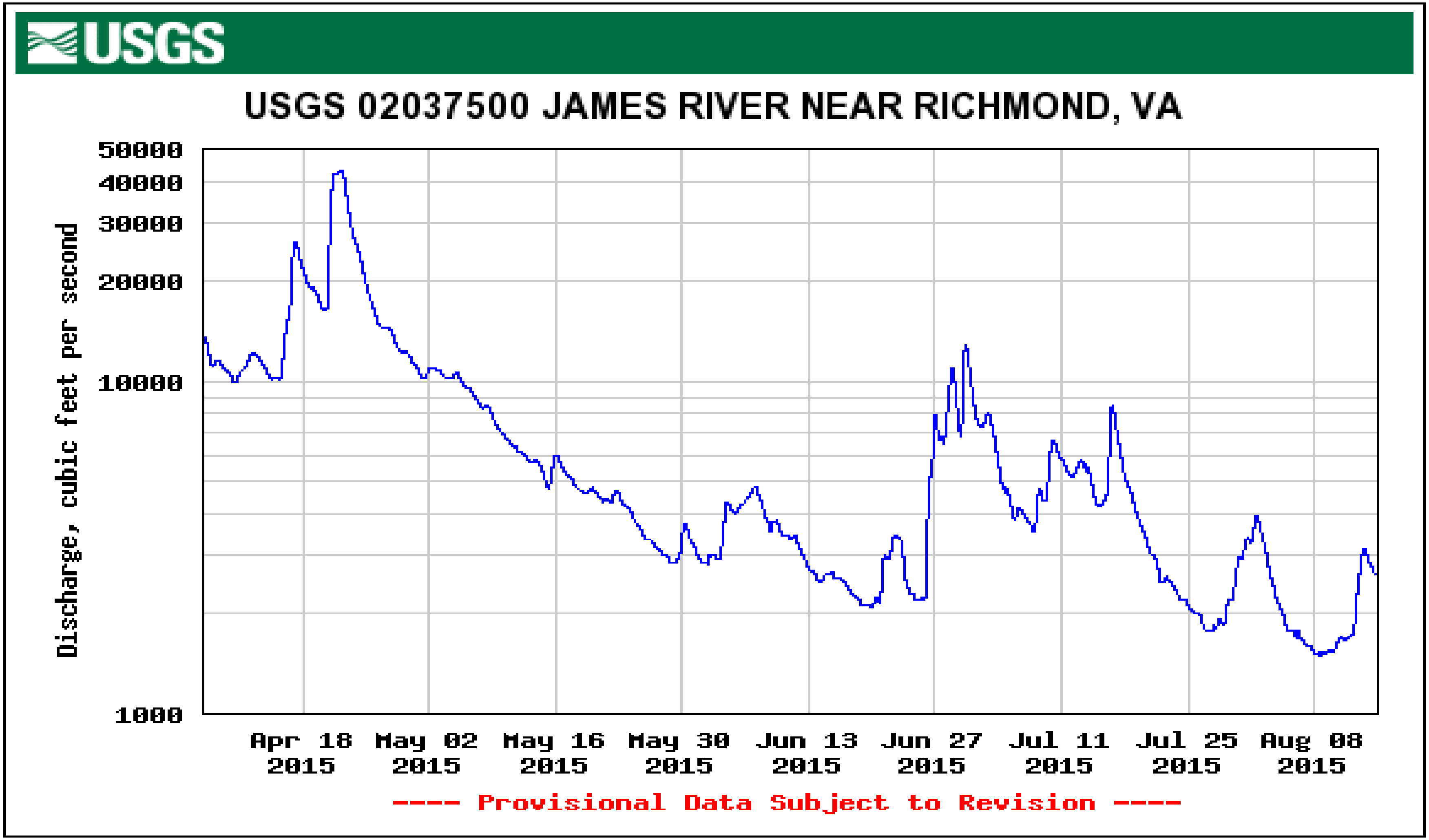

Hydrograph
Basin lag time
Peak flow
Rising limb
Recession limb
Overland flow
Through flow
Base flow
Discharge
3
2
1
4
3
2
0
12
24
36
48
30
72
Time

Watershed response to rainfall events: i.e **Rainfall-Runoff relationship**



Hydrograph: Flow or stage over time.

Gauged Watershed Data - Stream control structures with recording devices - records stage over time



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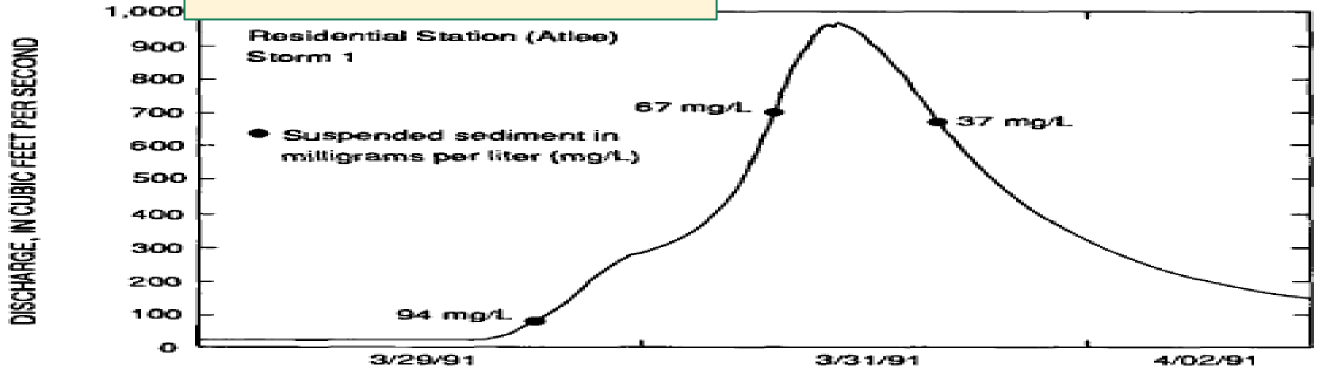
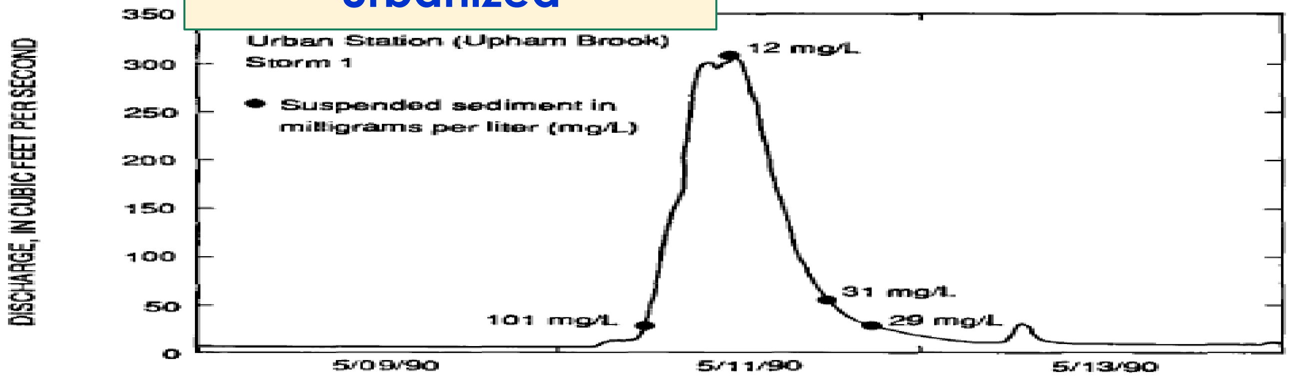
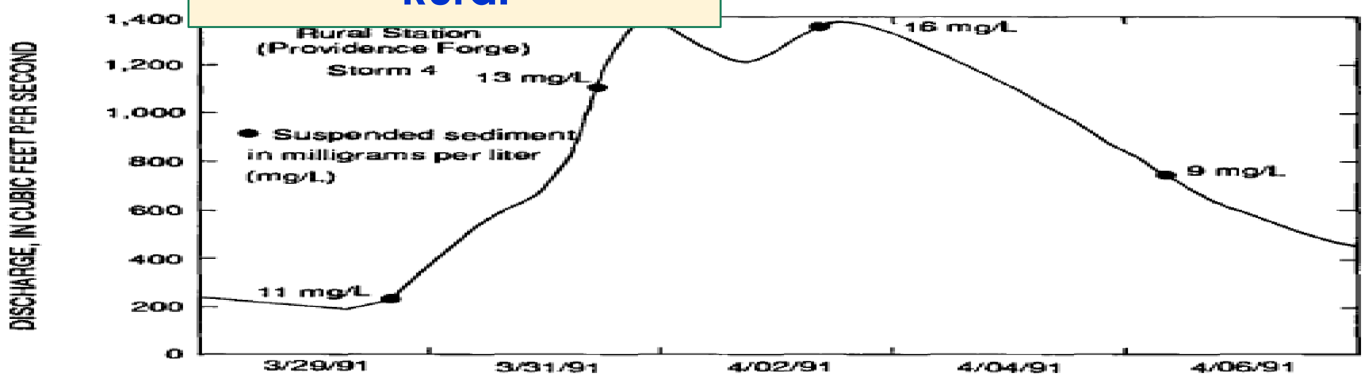
Residential



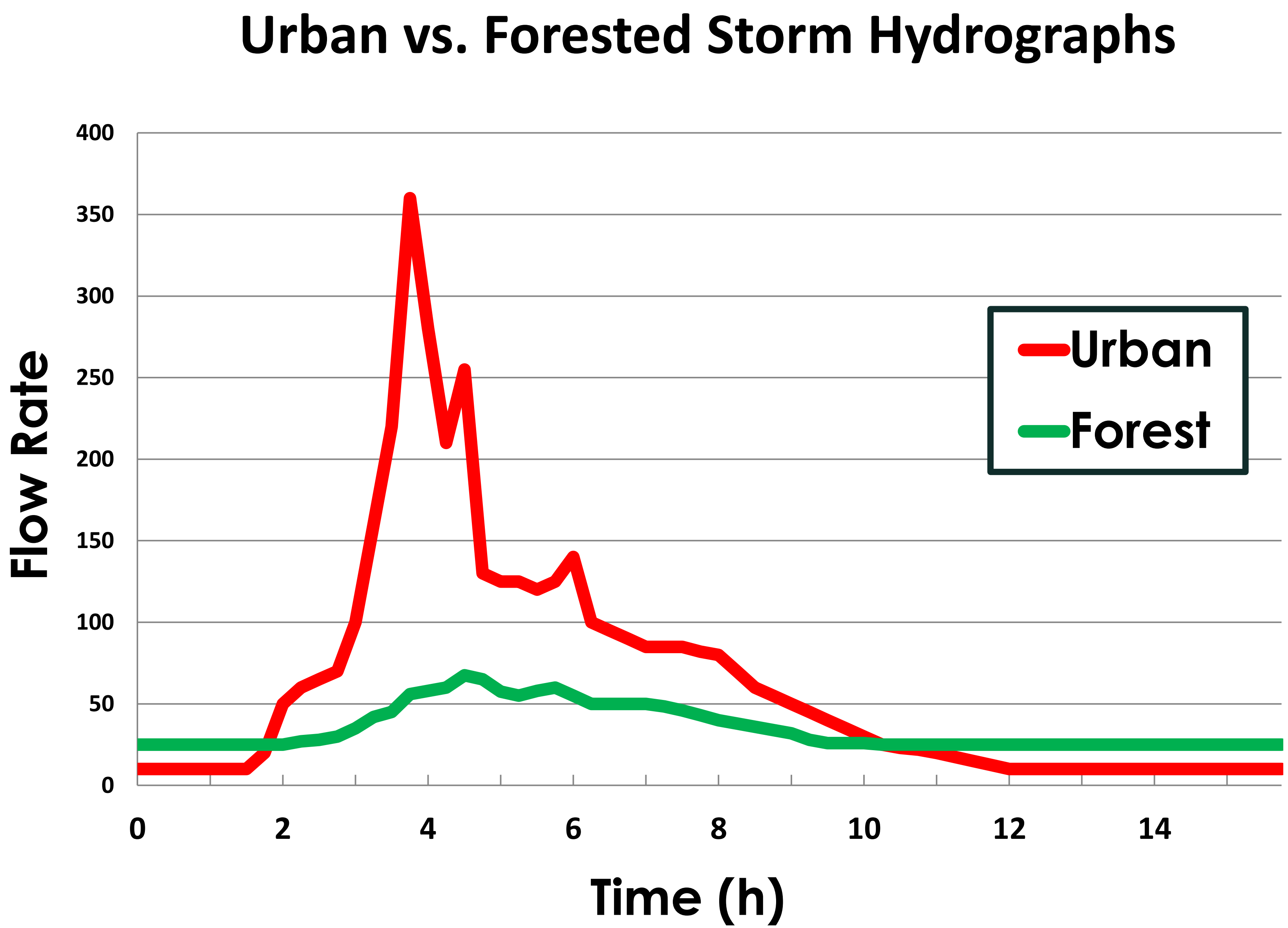
Urbanized



Rural



Mo


Urban vs. Forested Storm Hydrographs
400
350
300
250
200
150
100
50
0
Flow Rate
0
2
4
6
8
10
12
14
Time (h)
Urban
Forest

Rainfall-Runoff Relationships

- **Ungauged watersheds** - Impossible to collect data at every discharge point of interest.
- Create hydrographs by using synthetic methods
- Each method provides specific hydrograph parameters , i.e. discharge, volume

Rainfall-Runoff Relationships

- **Methods used for various design applications**
  - Rational Method
  - Modified Rational Method
  - NRCS TR-55
- **Different methods use different rainfall to runoff estimators**
  - CN, C-value, and runoff coefficient Rv

Rainfall-Runoff Coefficients

- C value (Rational), Rv (Simple Method), CN (TR-55)
- All take into account land cover types
- Only CN and Rv account for soil types

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Rational Method

Rational Formula:
Estimates peak rate of runoff

$$Q = C \times I \times A$$

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Rational Method

- **Runoff Coefficient, C**
  - Fraction of rainfall converted to runoff for specific land cover type
  - Coefficients found in many publications
- **Rainfall Intensity, I**
  - Rainfall Intensity (in/hr) for storm duration equal to time of concentration
  - **Intensity-Duration-Frequency** (I-D-F) curve, (calculate Tc, select return period)

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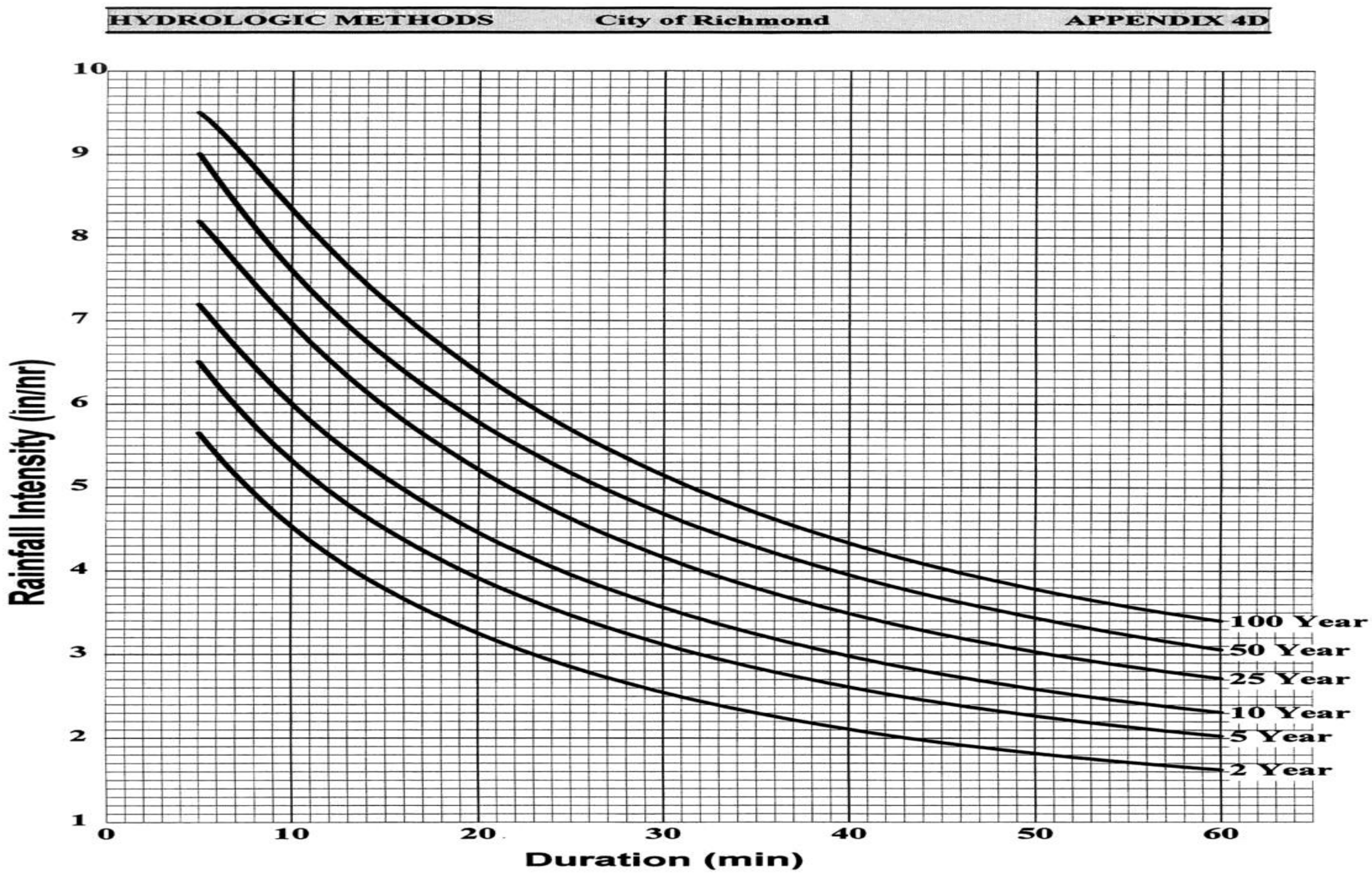
Rational Method

Rational Equation Runoff Coefficients

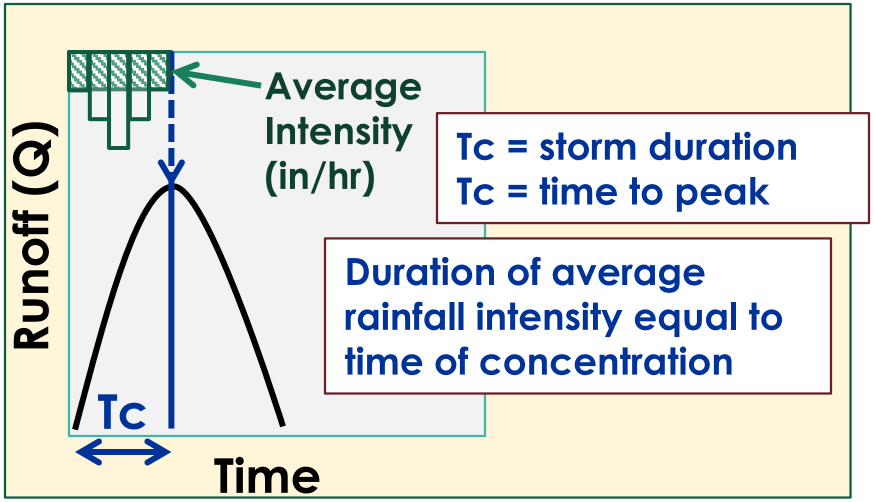
Land use	"C" Value
Business, industrial and commercial	0.90
Apartments	0.75
Schools	0.60
Residential - lots of 10,000 *sq. ft.*	0.50
- lots of 12,000 *sq. ft.*	0.45
- lots of 17,000 *sq. ft.*	0.45
- lots of ½ acre or more	0.40
Parks, cemeteries and unimproved areas	0.34
Paved and roof areas	0.90
Cultivated areas	0.60
Pasture	0.45
Forest	0.30
Steep grass slopes (2:1)	0.70
Shoulder and ditch areas	0.50
Lawns	0.20

I-D-F Curve for Richmond



Rational Method: Assumptions and Limitations

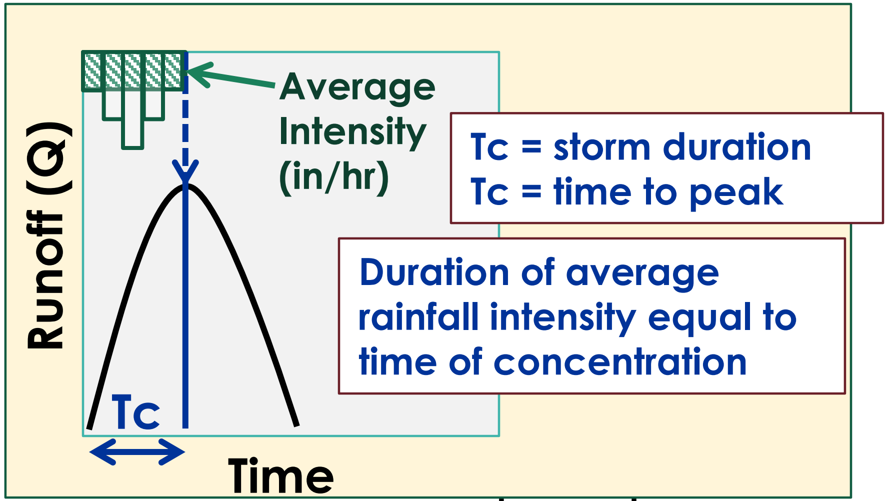
- Rainfall
  - duration equal to *Tc*



  - Coefficient "C" constant throughout storm
  - peak discharge of given frequency storm produced by average rainfall intensity over entire watershed

Rational Method: Assumptions and Limitations

- Frequency of rainfall and runoff events similar
- Rainfall
  - uniform intensity
  - duration equal to *Tc*
  - peak discharge of given frequency storm produced by average rainfall intensity
  - over entire area of watershed



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Rational Method

- Peak flow in cubic feet per min. only
- Design of culverts, inlets, etc
- No Volume
- No IDF or b,d,e constants for 1-year storm
- **Not well suited for VSMP compliance**

3c3: Modified Rational Method

Variation for sizing detention facilities

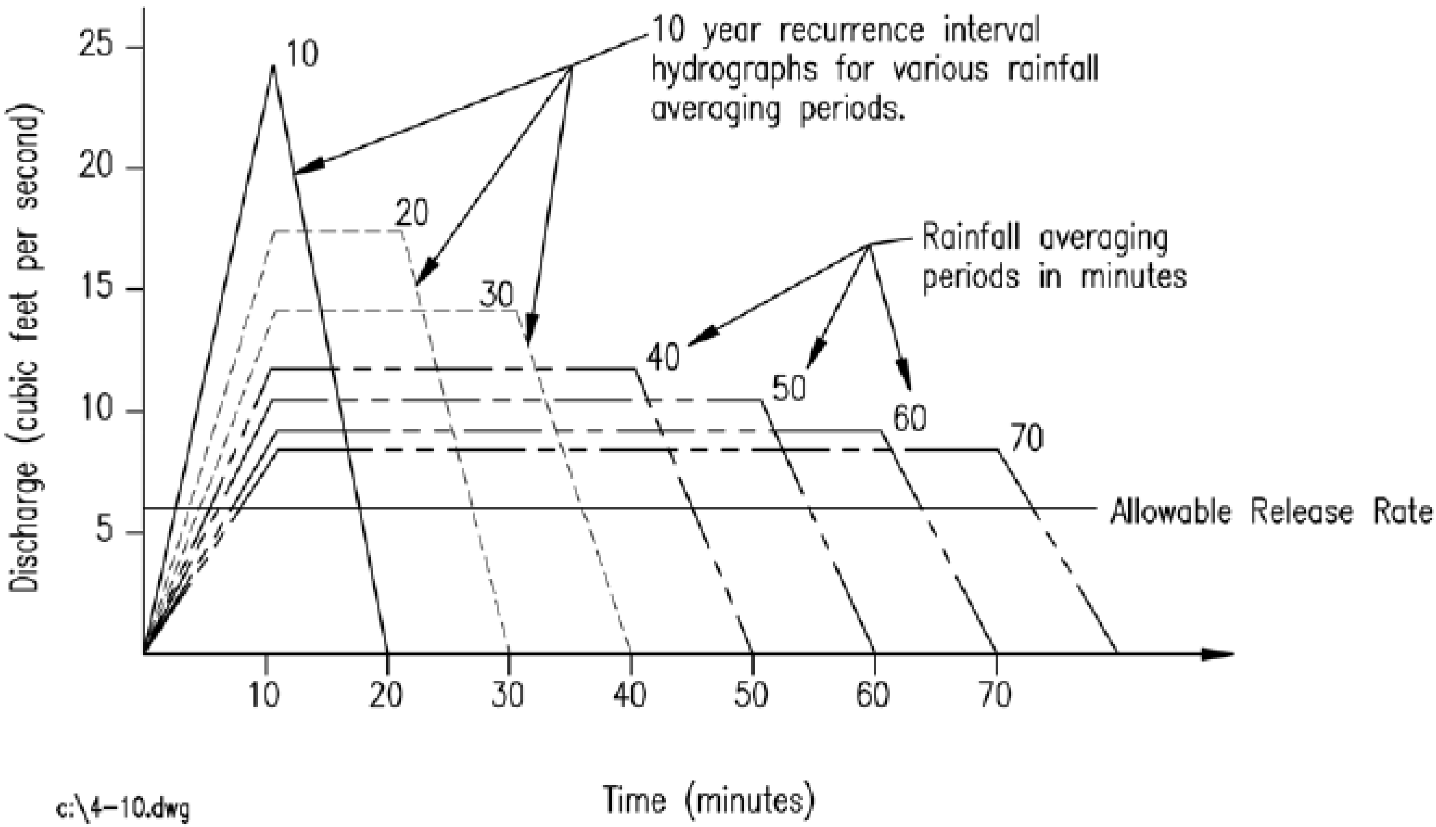
Iterative - Determine rainfall duration that produces **maximum storage volume**

Analyze different durations to find greatest storage volume

(**critical storm duration**)

3c: Modified Rational Method

Modified Rational Method Runoff Hydrographs
1999 SWM Handbook



MRM Maximum Storage Volume Calculations

Third step. Construct a series of hydrographs for each selected duration of the storm as shown in figure A9.1, Modified Rational Method Hydrographs. The estimated critical storage for this site is 88,858 cubic feet. Since the inflow volume must equal the outflow volume of 98,794 cubic feet, the time to the end of the release rate is 30.3. To reach zero outflow approximately 0.5 hours must be added so the total dewatering time will be about 30.3 hours. The outflow hydrograph reaches maximum flow at the intersection with the falling limb of the hydrograph resulting from a storm with a duration equal to the time of concentration.

<u>Table A9.2</u>

<u>Storage-Duration Values</u>

Duration of Storm (hr) (1)	Intensity I (in/hr) (2)	Peak Flow Q (cfs) (3)	Volume of Runoff (cuft) (4)	Release Flow Volume (cuft) (5)	Required Storage Volume (cuft) (6)
0.25	4.8	39.9	35,925	828	35,097
0.50	3.4	28.3	50,894	1,656	49,238
0.75	2.7	22.5	60,624	2,484	58,140
1.00	2.3	19.1	68,856	3,312	65,544
1.50	1.7	14.1	76,341	4,968	71,373
2.00	1.4	11.6	83,825	6,624	77,201
3.00	1.1	9.1	98,794	9,936	88,858 << Maximum Storage Volume Required
3.50	0.9	7.5	94,303	11,592	82,711

Column (3) Peak Flow = Q = c i a
example : 0.7 X 4.8 X 11.88 = 39.9 cfs

Column (4) Runoff Volume = Q (col 3) X Duration of Storm (col. 1) X 3600
example : 39.9 cfs X 0.25 hrs X 3600 = 35,925 cuft

Column (5) Release Volume = 0.92 cfs X Duration of Storm (col. 1) X 3600
example : 0.92 X 0.25 X 3600 = 828 cuft

Column (6) Required Storage = Runoff Volume (col. 4) - Release Volume (col 5)
example : 35,925 - 828 = 35,097

3c: Modified Rational Method

- Design of retention/detention facilities
- Provides volume based on sizing
- Storm duration corresponds to critical volume
- Not 24 hours duration

Urban Hydrology for Small Watersheds (TR-55)

NRCS publication Technical Release Number 55 (TR-55): Urban Hydrology for Small Watersheds, 2nd edition (June 1986)

See Resources Section for link to TR-55 manual Review!

Peak Discharge

PG 4,25

$$q_p = q_u A_m Q F_p$$

TR-55 presents two methods for estimating peak discharge

Graphical Method

Provides:

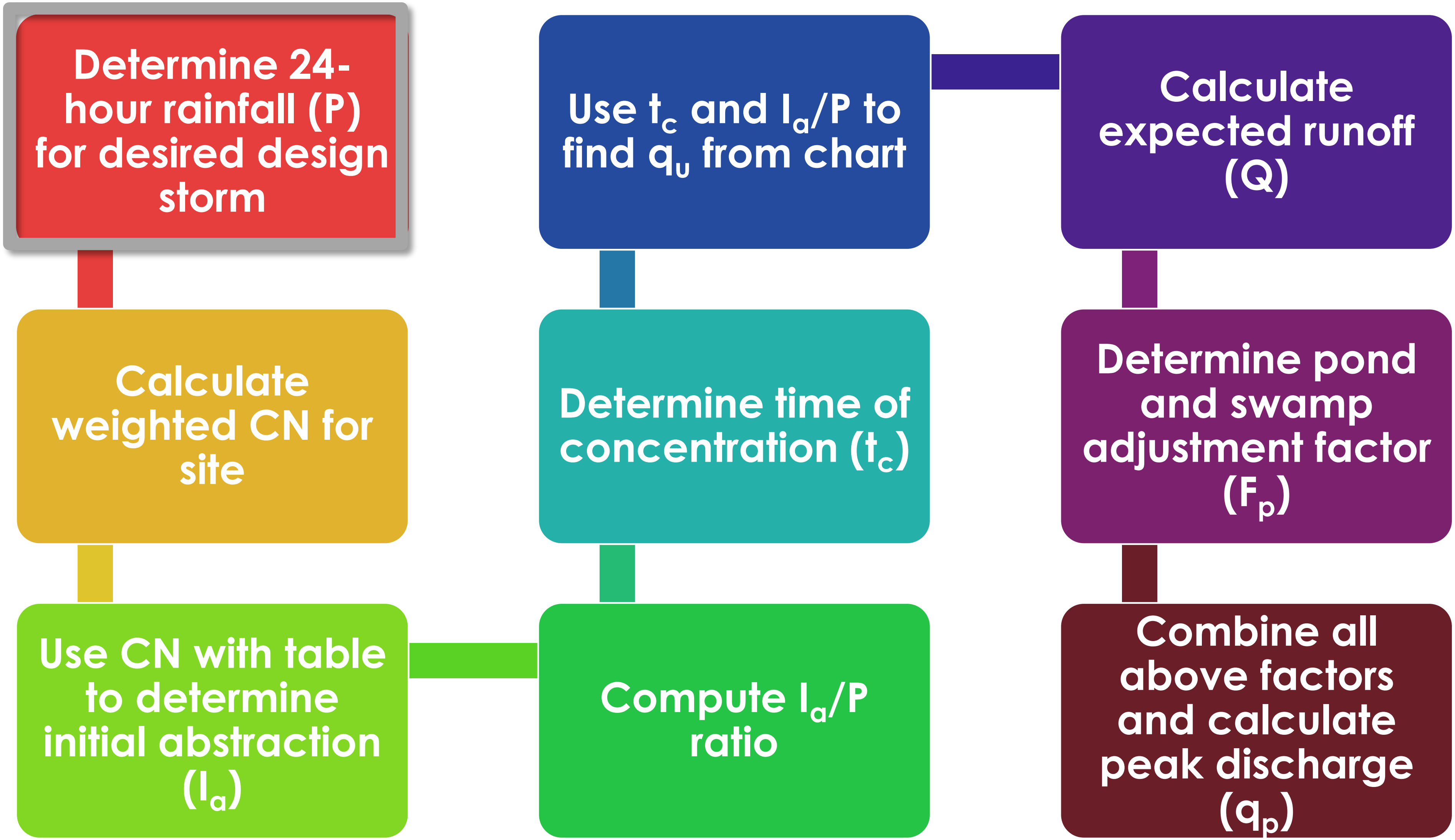
peak discharge and **runoff volume**

Tabular Method

Provides:

peak discharge, runoff volume, and a **runoff hydrograph**

TR-55 Graphical Peak Discharge Method



Determine rainfall

- Precipitation
  - NOAA Atlas 14
  - Distribution

Determine rainfall

NOAA Atlas 14, Volume 2, Version 3
Location name: Petersburg, Virginia, US*
Latitude: 37.1953°, Longitude: -77.3657°

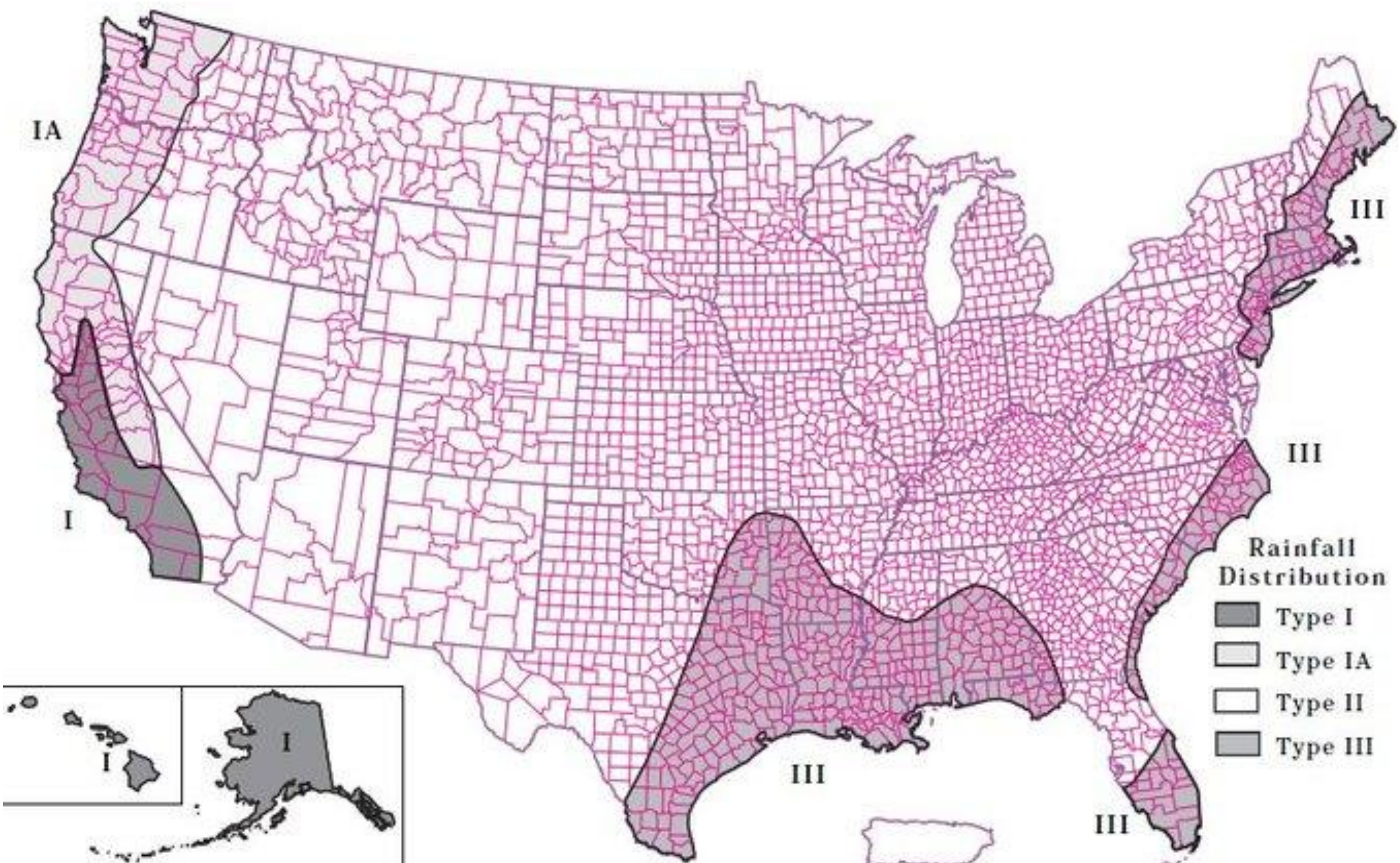
POINT PRECIPITATION FREQUENCY ESTIMATES

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Average recurrence interval (years)						
	1	2	5	10	25	50	100
10-min	0.616 (0.553-0.689)	0.727 (0.654-0.810)	0.845 (0.760-0.941)	0.951 (0.853-1.06)	1.07 (0.951-1.18)	1.16 (1.03-1.29)	1.24 (1.10-1.38)
15-min	0.770 (0.691-0.861)	0.913 (0.822-1.02)	1.07 (0.961-1.19)	1.20 (1.08-1.34)	1.35 (1.21-1.50)	1.46 (1.30-1.63)	1.57 (1.39-1.74)
30-min	1.06 (0.948-1.18)	1.26 (1.14-1.41)	1.52 (1.37-1.69)	1.74 (1.56-1.94)	2.00 (1.79-2.22)	2.21 (1.96-2.45)	2.40 (2.12-2.67)
60-min	1.32 (1.18-1.47)	1.58 (1.43-1.76)	1.95 (1.75-2.17)	2.27 (2.04-2.53)	2.66 (2.38-2.96)	2.99 (2.66-3.32)	3.31 (2.93-3.67)
2-hr	1.57 (1.40-1.76)	1.89 (1.69-2.11)	2.34 (2.10-2.62)	2.76 (2.47-3.08)	3.30 (2.93-3.67)	3.76 (3.32-4.18)	4.22 (3.70-4.69)
3-hr	1.69 (1.50-1.90)	2.03 (1.81-2.28)	2.52 (2.26-2.83)	2.99 (2.66-3.35)	3.58 (3.17-4.01)	4.09 (3.60-4.58)	4.63 (4.04-5.16)
6-hr	2.03 (1.81-2.31)	2.44 (2.17-2.76)	3.04 (2.70-3.43)	3.61 (3.19-4.07)	4.36 (3.84-4.91)	5.03 (4.39-5.64)	5.72 (4.96-6.41)
12-hr	2.42 (2.16-2.76)	2.91 (2.60-3.30)	3.64 (3.24-4.12)	4.35 (3.85-4.91)	5.32 (4.67-5.98)	6.19 (5.39-6.94)	7.11 (6.14-7.96)
24-hr	**2.80 (2.56-3.09)**	**3.40 (3.11-3.75)**	4.36 (3.98-4.81)	**5.17 (4.70-5.70)**	6.35 (5.74-6.99)	7.36 (6.61-8.10)	8.46 (7.54-9.30)

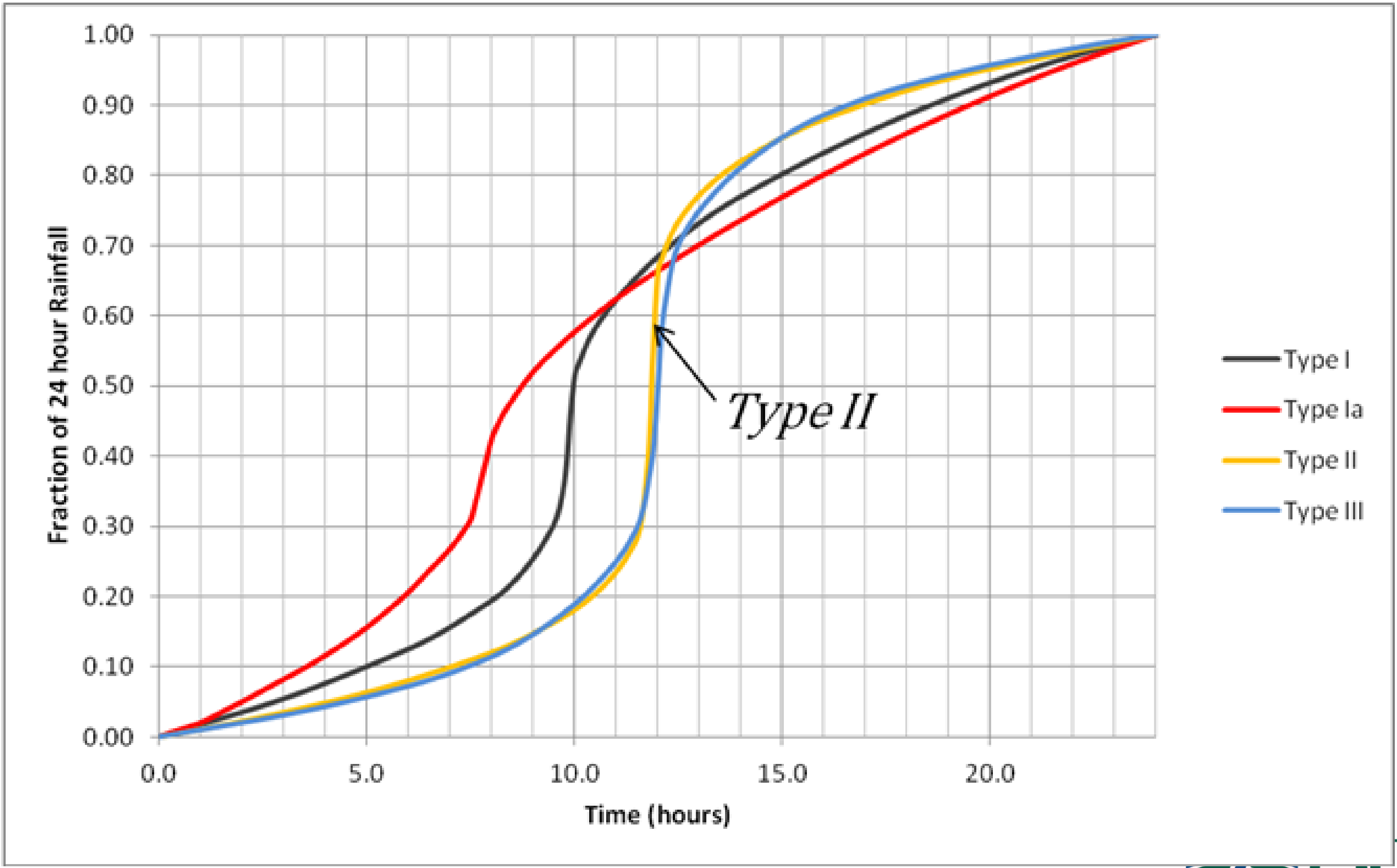
Determine rainfall

Precipitation - Distribution



Determine rainfall

Precipitation - Distribution



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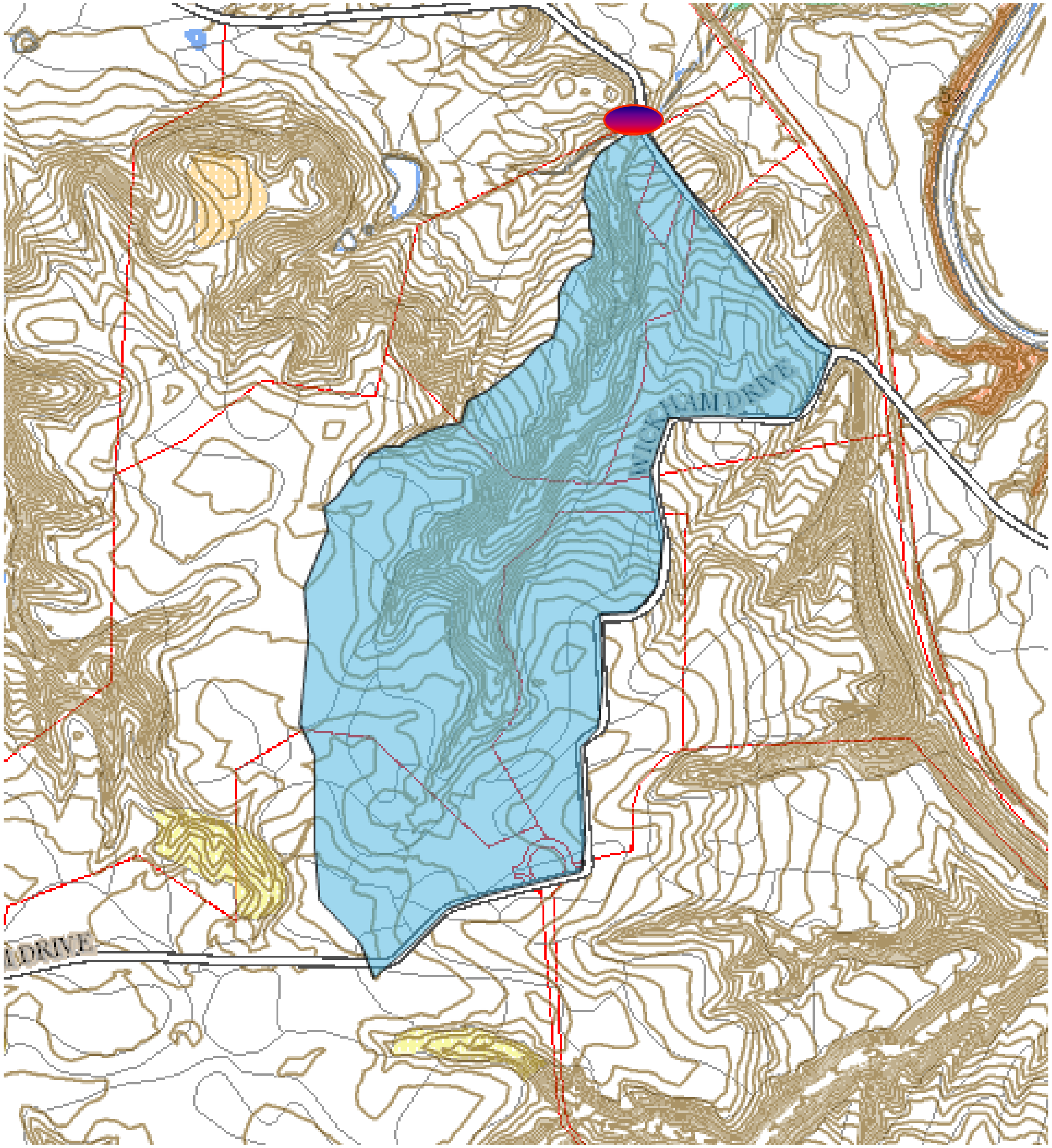
TR-55 Graphical Peak Discharge Method

- Determine 24-hour rainfall (P) for desired design storm
- Calculate weighted CN for site
- Use CN with table to determine initial abstraction (I_a)
- Compute I_a/P ratio
- Determine time of concentration (t_c)
- Use t_c and I_a/P to find q_u from chart
- Calculate expected runoff (Q)
- Determine pond and swamp adjustment factor (F_p)
- Combine all above factors and calculate peak discharge (q_p)

CN indicates runoff potential of an area



Watershed Delineation:

- Choose watershed outlet point
- Delineate watershed boundary (perpendicular lines across contour lines draining to point of interest)

Note - A watershed boundary always runs perpendicular to contour lines

- CN determination:
  - Soils
  - Hydrologic conditions
  - (good, fair, poor)
  - Cover type
  - Treatment (sometimes)

- CN determination:
  - 4 Curve Number Tables
    - Urban

      Cover type- vegetation, bare soil, and impervious surfaces.
    - cultivated agricultural lands
    - other agricultural lands
    - arid and semiarid rangelands

weighted CN

- **Treatment -** cover type modifier for agricultural (contouring, terracing)
  - **For ag and arid/semiarid**

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Hydrologic Soil Groups

Group A: Low runoff potential

Group B: Moderately low runoff potential

Group C: Moderately high runoff potential

Group D: High runoff potential

weighted CN

Table 3-2 Runoff CNs for Urban Areas

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82

weighted CN

PG 13

Table 3-3 Runoff Curve Numbers for Other Agricultural Lands

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.

weighted CN

Determine a composite curve number given the following data:

24 acres - open space, soil c

16 acres - 1/2 acre lots, 25% impervious, good condition, soil b

18 acres - woods Soil D

Solution : (24*74) +(16*70)+(18*77) =

1776+1120+1386=4282/58= 73.8 Round to 74

weighted CN

Additional factors that can further adjust curve numbers

- Antecedent runoff condition
  - Index of runoff potential before a storm event
- **Urban impervious area modifications**
  - **Connected impervious areas**
  - Unconnected impervious

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weighted CN

Connected impervious area:

- Runoff flows directly to drainage system; or
- Runoff is **concentrated shallow flow** over pervious area and then into drainage system

Unconnected impervious area:

- Runoff from impervious area is spread over pervious area as **sheet flow** before discharging to drainage system

- Connected vs. unconnected
  - **Total impervious area < 30% and**
    Impervious area **not directly connected**
    - *designer can use Figure 2-4 of TR-55 to determine CN (Fig. 3-4 in PG)*
  - **Total impervious area ≥ 30%**
    Impervious area considered **connected**
    - *designer can use Figure 2-3 from TR-55 to adjust CN (Fig. 3-3 in PG)*

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TR-55 Graphical Peak Discharge Method

Determine 24-hour rainfall (P) for desired design storm

Calculate weighted CN for site

Use CN with table to determine initial abstraction (I_a)

Calculate expected runoff (Q)

Determine time of concentration (t_c)

Compute I_a/P ratio

Use t_c and I_a/P to find q_u from chart

Determine pond and swamp adjustment factor (F_p)

Combine all above factors and calculate peak discharge (q_p)

initial abstraction (I_a)

TABLE 5-9

I_a VALUES FOR RUNOFF CURVE NUMBERS

Curve Number	I_a (inches)	Curve Number	I_a (inches)	Curve Number	I_a (inches)
40	3.000	60	1.333	80	0.500
41	2.878	61	1.279	81	0.469
42	2.762	62	1.226	82	0.439
43	2.651	63	1.175	83	0.410
44	2.545	64	1.125	84	0.381
45	2.444	65	1.077	85	0.353
46	2.348	66	1.030	86	0.326
47	2.255	67	0.985	87	0.299
48	2.167	68	0.941	88	0.273
49	2.082	69	0.899	89	0.247
50	2.000	70	0.857	90	0.222
51	1.922	71	0.817	91	0.198
52	1.846	72	0.778	92	0.174
53	1.774	73	0.740	93	0.151
54	1.704	74	0.703	94	0.128
55	1.636	75	0.667	95	0.105
56	1.571	76	0.632	96	0.083
57	1.509	77	0.597	97	0.062
58	1.448	78	0.564	98	0.041
59	1.390	79	0.532		

- Look up Ia values in TR-55

initial abstraction (I_a)

Runoff Volume (Q)

$$q_p = q_u A_m Q F_p$$

$$Q = \frac{\left(P - I_a\right)^2}{\left(P - I_a\right) + S}$$

Q = Runoff (in)

P = Rainfall (in)

S = Potential maximum retention after runoff begins (in)

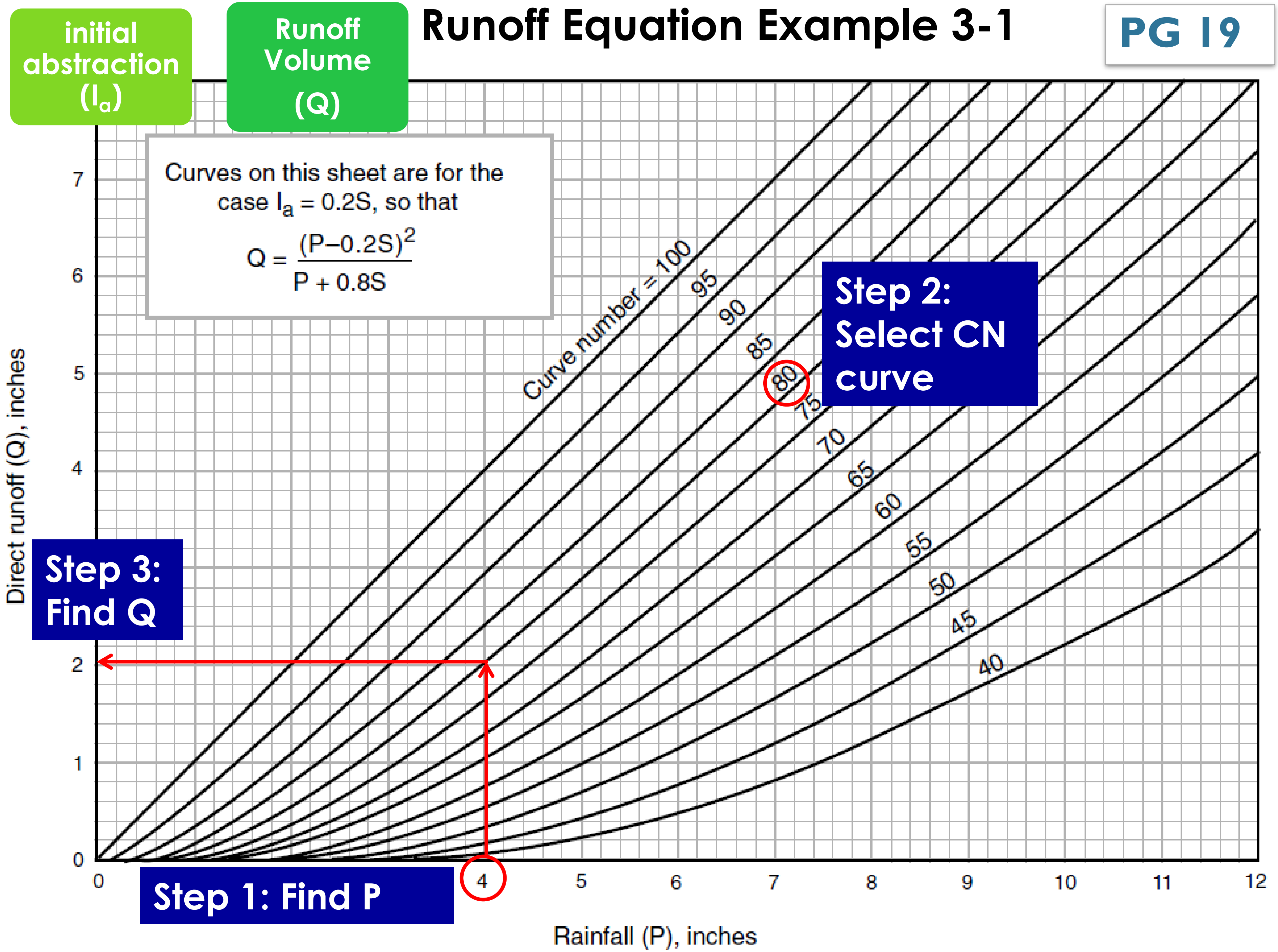
$$S = \left(\frac{1000}{CN}\right) - 10$$

CN = Curve number

I_a = Initial abstraction (in)

= 0.2 x S (all losses before runoff begins)

Runoff Equation Example 3-1



initial abstraction (I_a)

Runoff Volume (Q)

Runoff Equation Example 3-2

PG 20

Runoff depth for curve number of—

Rainfall	40	45	50	55	60	65	70	75	80	85	90	95	98
	inches												
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	[illegible]	[illegible]	[illegible]	[illegible]
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	[illegible]	[illegible]	[illegible]	[illegible]
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
[illegible]	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	[illegible]	[illegible]	[illegible]	4.26
[illegible]	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	[illegible]	[illegible]	[illegible]	4.76
[illegible]	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	[illegible]	[illegible]	[illegible]	5.76
7.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.23	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

Step 1:
Find P

Step 2:
Select CN column

Step 3:
Determine Q

initial abstraction (I_a)

Runoff Volume (Q)

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

- Runoff equation
  - Used to express how much runoff volume generated by certain volume of rainfall
  - Attempts to quantify losses before runoff begins
  - Runoff computed is fraction of rainfall
  - **Used to connect water quality to water quantity in VRRM**

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Runoff Exercise:

Use the 3 methods: Table, Graph, and Equations

Given a watershed with a CN of 90, what would be the direct runoff (Q) from a rainfall (P) of 4.0 inches?

P = rainfall (in)
CN = runoff curve number

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Runoff Equation Example 3-2

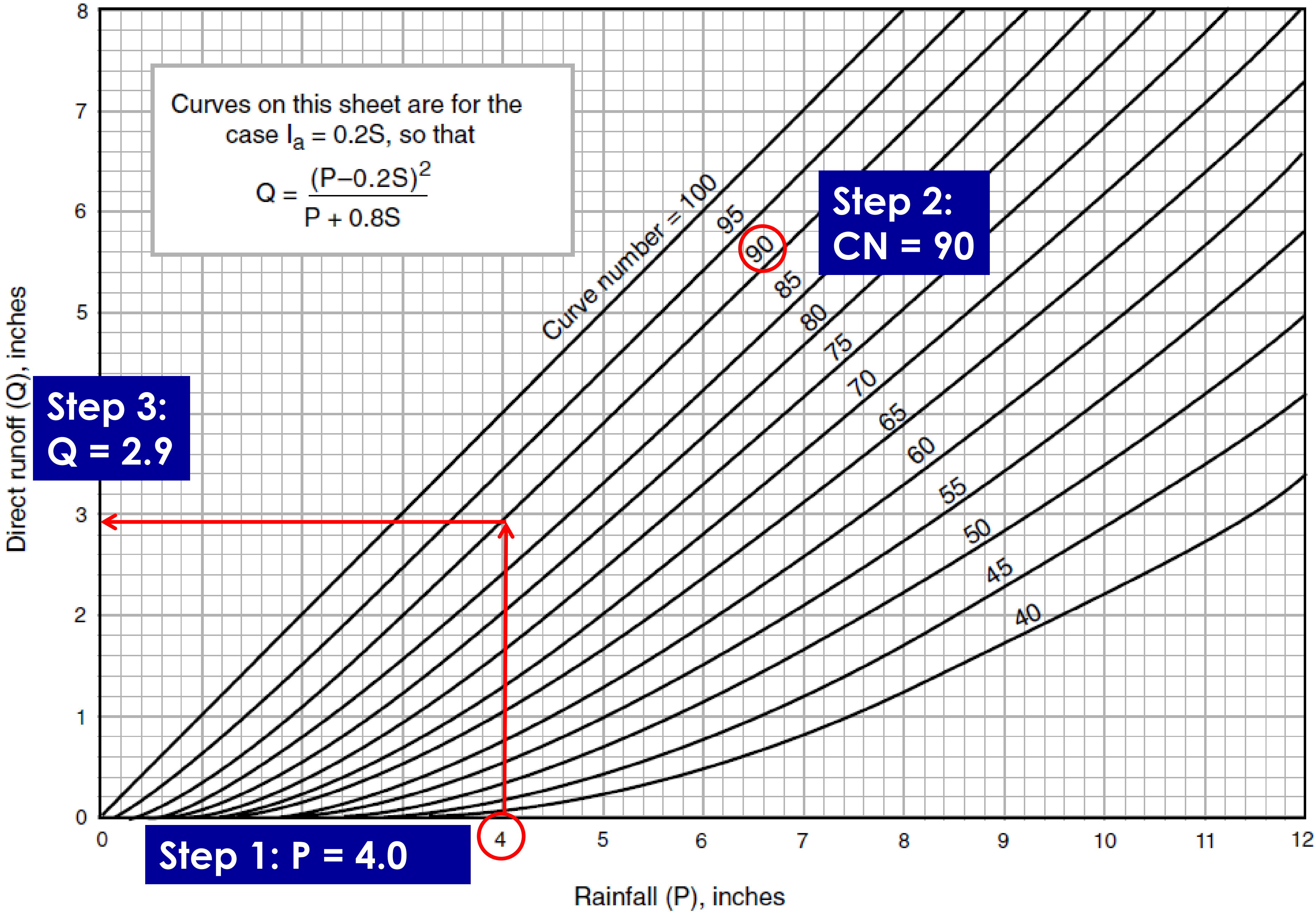
Rainfall	Runoff depth for curve number of—												
	40	45	50	55	60	65	70	75	80	85	90	95	98
	inches												
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	[illegible]	[illegible]
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	.27	.46	[illegible]	[illegible]
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
[illegible]	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	[illegible]	[illegible]
[illegible]	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	[illegible]	[illegible]
[illegible]	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	[illegible]	[illegible]
7.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

Step 1:
P = 4.0

Step 2:
CN = 90

Step 3:
Q = 2.92

Runoff Equation Example 3-1



Runoff Equation Example 3-1

P = rainfall (in)

CN = runoff curve number

S = potential maximum retention after runoff begins (in)

$$S = \left(\frac{1000}{CN}\right) - 10 = \left(\frac{1000}{90}\right) - 10 = 1.1$$

I_a= initial abstraction (in) = **0.2 x S = 0.2 x 1.1 = 0.22**

$$Q = \frac{(P - 1_a)^2}{(P - 1_a) + S} = \frac{(4.0 - 0.22)^2}{(4.0 - 0.22) + 1.1} = 2.93$$

TR-55 Graphical Peak Discharge Method

1. Determine 24-hour rainfall (P) for desired design storm
2. Calculate weighted CN for site
3. Use CN with table to determine initial abstraction (I_a)
4. Calculate expected runoff (Q)
5. Determine time of concentration (t_c)
6. Compute I_a/P ratio
7. Use t_c and I_a/P to find q_u from chart
8. Determine pond and swamp adjustment factor (F_p)
9. Combine all above factors and calculate peak discharge (q_p)

T_c Time of Concentration, Travel Time

Travel time (T_t):

Time it takes water to travel from one location to another in a watershed

Time of concentration (T_c):

Time required for water to travel from most hydraulically distant point in watershed to point of analysis

(runoff from entire watershed contributing)

Sum of time increments for each flow segment

T_c = Σ (overland flow + shallow concentrated flow + channel flow)

T_c

Flow segments

Overland (Sheet) Flow Manning's kinematic solution	Shallow flow	Upper reaches of hydraulic flow path
Shallow Concentrated Flow Graphical solution	Overland flow converges to form defined flow	Flow Paths w/o defined channel
Channel Flow Manning's Equation	Flow converges in natural or manmade conveyances	Well defined drainageway

T_c

Overland Flow: NRCS TR-55 Method

$$Tt = 0.007 \times \frac{(nL)^{0.8}}{P_2^{0.5} \times s^{0.4}}$$

L **= length of overland flow (feet)**

n **= Manning's roughness coefficient**

P_2 **= 2 year, 24-hour rainfall in inches (NOAA Atlas 14)**

s **= slope (feet/feet)**

T_c

Shallow Concentrated Flow: NRCS TR-55 Method

- Occurs where overland flow converges to form small rills, gullies, and swales
- Flow length 0 to 1000 feet maximum

T_c

Shallow Concentrated Flow: NRCS TR-55 Method

$$Tt = \left(\frac{L}{V \times t} \right)$$

L **= flow length (feet)**

V **= average velocity (feet/second)**

t **= conversion factor**

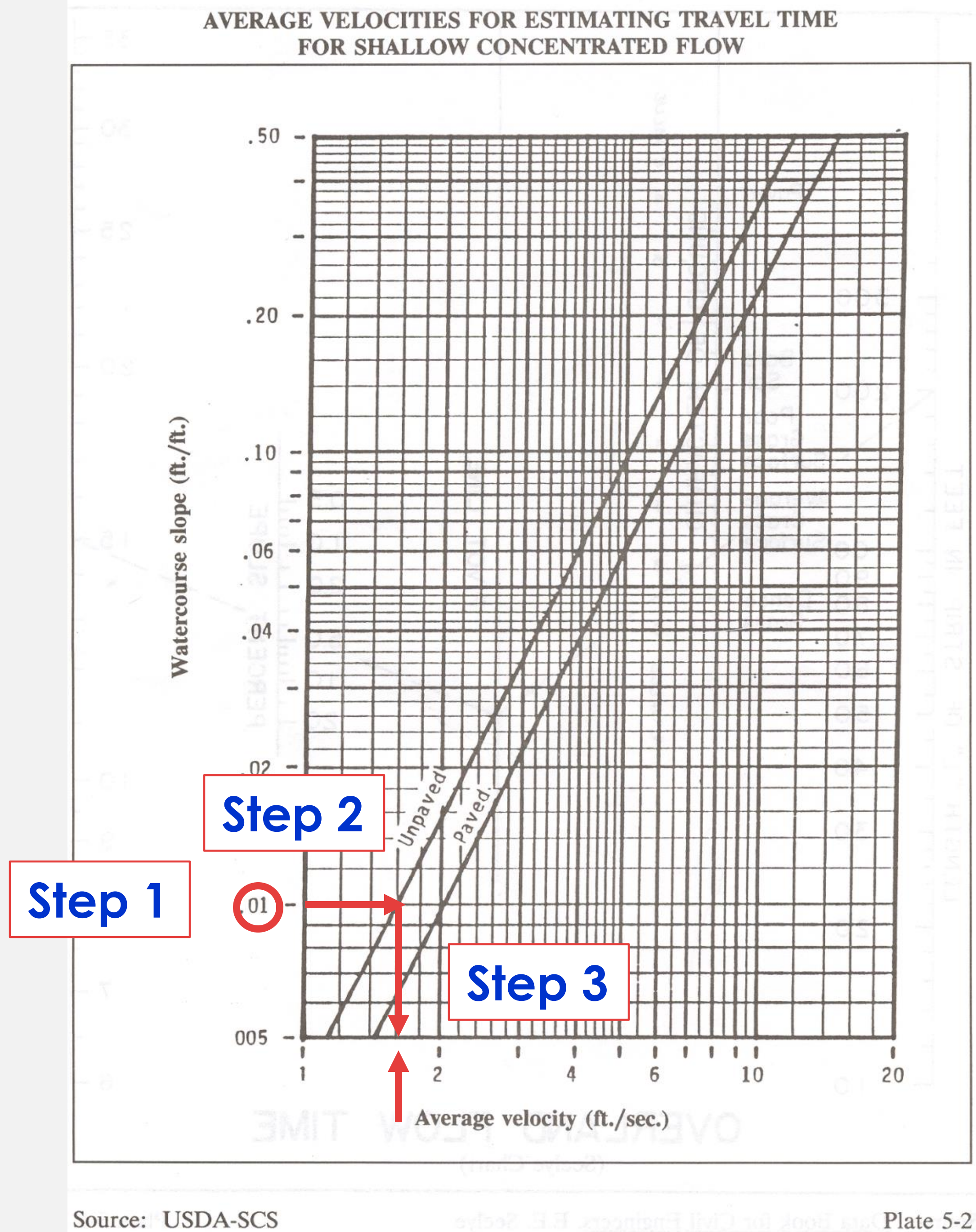
T_c

Example:

- 1% slope (0.01 ft/ft)
- Unpaved
- Length = 200 ft

Answer:

- ✓ *V* = 1.6 ft/second
- ✓ *Tt* = 200/(1.6 x 60)
  = 2.1 minutes



T_c Channel Flow

- Occurs where concentrated flow occurs in channels with well-defined cross-section (streams, ditches, gutters, pipes, etc.)
- Use velocity from Manning's equation for open channel flow:

$$V = \frac{1.49}{n} \times R^{(2/3)} \times \sqrt{s}$$

V = velocity (fps)
n = Manning's roughness coef.
R = hydraulic radius (A/P)
A= wetted cross sectional area
P=wetted perimeter(ft)
s = slope (ft/ft)

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T_c

Channel Flow

$$Tt = \left(\frac{L}{V} \right)$$

***L* = channel flow length** (feet)

***V* = average velocity**(feet/second)

→ ***use Manning's equation***

$$V = \frac{1.49}{n} \times R^{(2/3)} \times \sqrt{s}$$

T_c

Worksheet 3: Time of Concentration (T_c) or travel time (T_t)

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed

Check one: ☐ T_c ☐ T_t through subarea

Notes: Space for as many as two segments per flow type can be used for each worksheet.
Include a map, schematic, or description of flow segments.

SHEET FLOW (Tc only)

Segment ID		
1. Surface description (table 3-1)		
2. Manning's roughness coefficient, n (table 3-1)		
3. Flow length, L (total L † 300 ft) .... ft		
4. Two-year 24-hour rainfall, P_2 .... in		
5. Land slope, s .... ft/ft		
6. $T_t = \frac{0.007\ (nL)^{0.8}}{P_2^{\ 0.5}\ s^{0.4}}$ Compute T_t .... hr	+	=

SHALLOW CONCENTRATION FLOW

Segment ID		
7. Surface description (paved or unpaved)		
8. Flow length, L ....ft		
9. Watercourse slope, s .... ft/ft		
10. Average velocity, V (figure 3-1) .... ft/s		
11. $T_t = \frac{L}{3600\ V}$ Compute T_t .... hr	+	=

CHANNEL FLOW

Segment ID		
12. Cross sectional flow area, a .... ft^2		
13. Wetted perimeter, p_w .... ft		
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r .... ft		
15 Channel slope, s .... ft/ft		
16. Manning's roughness coefficient, n		
17. $V = \frac{1.49\ r^{2/3}\ s^{1/2}}{n}$ Compute V ....ft/s		
18. Flow length, L .... ft		
19. $T_t = \frac{L}{3600\ V}$ Compute T_t .... hr	+	=

20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) .... Hr ☐

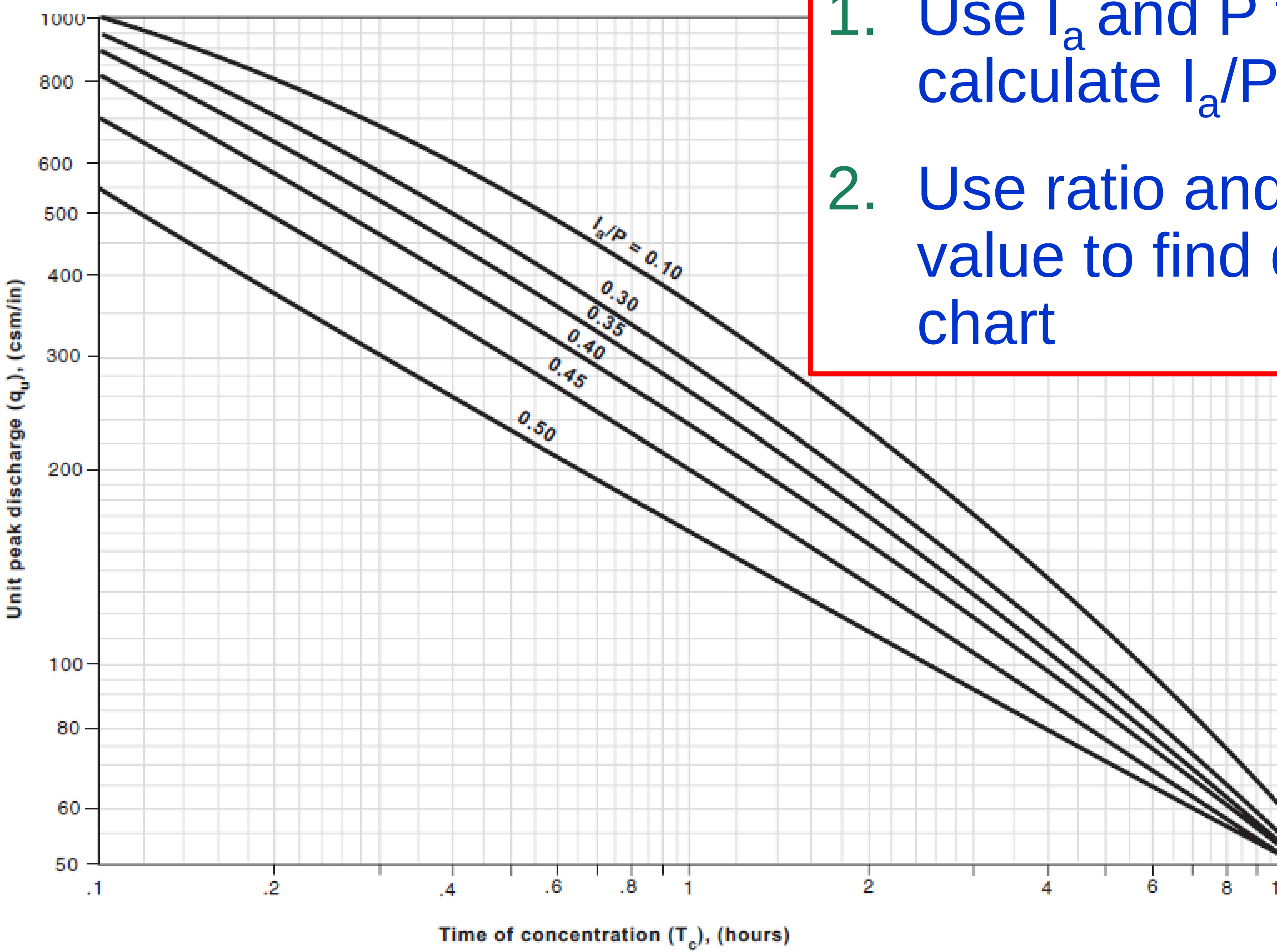
Module 3

TR-55 Graphical Peak Discharge Method

1. Determine 24-hour rainfall (P) for desired design storm
2. Calculate weighted CN for site
3. Use CN with table to determine initial abstraction (I_a)
4. Calculate expected runoff (Q)
5. Determine time of concentration (t_c)
6. Compute I_a/P ratio
7. Use t_c and I_a/P to find q_u from chart
8. Determine pond and swamp adjustment factor (F_p)
9. Combine all above factors and calculate peak discharge (q_p)

Find q_u on chart -

Exhibit 4-II Unit peal discharge (q_u) for NRCS (SCS) type II rainfall distribution



1. Use I_a and P to calculate I_a/P ratio
2. Use ratio and T_c value to find q_u from chart

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TR-55 Graphical Peak Discharge Method

- Determine 24-hour rainfall (P) for desired design storm
- Calculate weighted CN for site
- Use CN with table to determine initial abstraction (I_a)
- Calculate expected runoff (Q)
- Determine time of concentration (t_c)
- Compute I_a/P ratio
- Use t_c and I_a/P to find q_u from chart
- Determine pond and swamp adjustment factor (F_p)
- Combine all above factors and calculate peak discharge (q_p)

Pond & Swamp Adjustment

$q_p = q_u A_m Q F_p$

- Factor needed **<u>if</u>** ponds and/or swamps scattered throughout watershed, but not on path used to determine Tc

- Determine percentage of drainage area represented by swamps and/or ponds

TABLE 5-10

ADJUSTMENT FACTOR (F_p) FOR POND AND SWAMP AREAS SPREAD THROUGHOUT THE WATERSHED

Percentage of pond and swamp areas	F_p
0	1.00
0.2	0.97
1.0	0.87
3.0	0.75
5.0	0.72

TR-55 Graphical Peak Discharge Method

1. Determine 24-hour rainfall (P) for desired design storm
2. Calculate weighted CN for site
3. Use CN with table to determine initial abstraction (I_a)
4. Calculate expected runoff (Q)
5. Determine time of concentration (t_c)
6. Compute I_a/P ratio
7. Use t_c and I_a/P to find q_u from chart
8. Determine pond and swamp adjustment factor (F_p)
9. Combine all above factors and calculate peak discharge (q_p)

peak discharge (q_p)

Calculate peak discharge

$$q_p = q_u A_m Q F_p$$

- q_p (cfs)
- q_u (csm/in) from previous step
- Q (in) from previous step
- A_m (m^2) from site plan
- F_p from previous step

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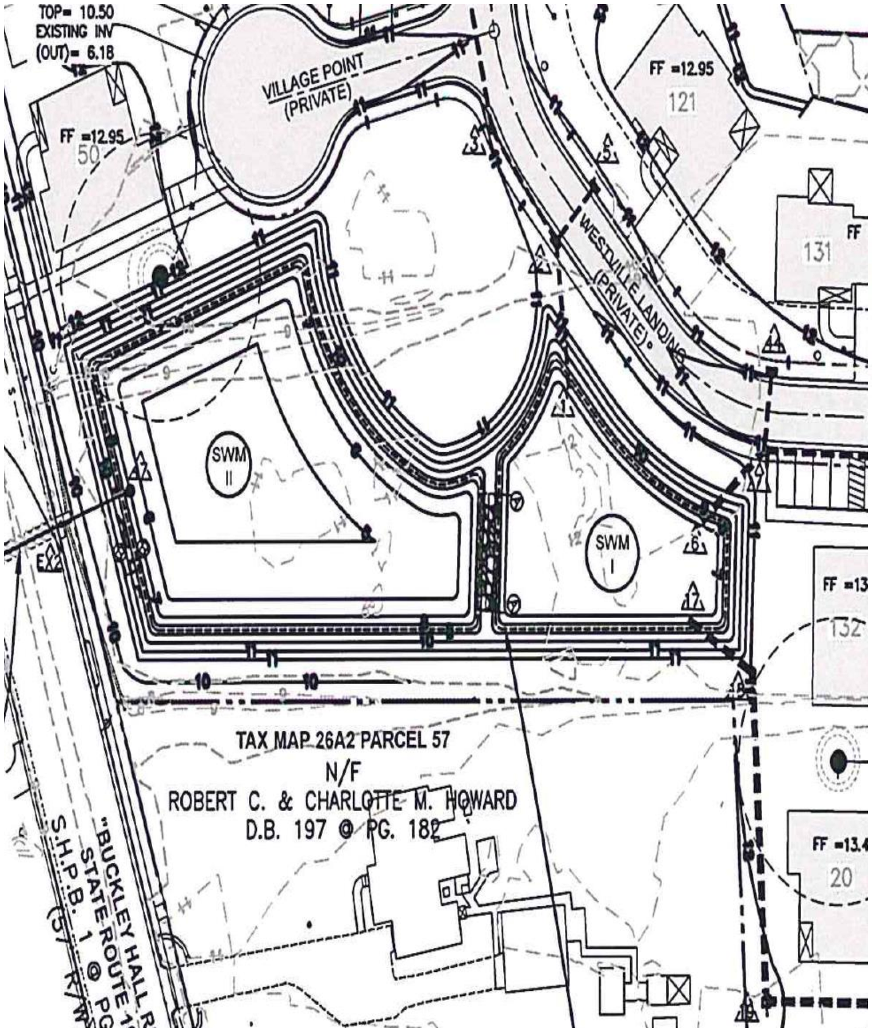
Routing of Peak Control Facilities

- What does a reviewer look for?
  - Inflow Hydrograph
  - Stage-storage curve
    - Area or Volume
  - Stage- discharge curve (flow changes with depth)
    - Weir equation
    - Orifice equation
    - Pipe flow
  - Outflow Hydrograph

Stage- Storage



Elevation (feet)	Surf.Area (sq-ft)	Inc.Store (cubic-feet)	Cum.Store (cubic-feet)
5.00	4,534	0	0
6.00	11,081	7,808	7,808
7.00	19,742	15,412	23,219
7.25	20,372	5,014	28,233
8.00	22,357	16,023	44,257
8.50	23,723	11,520	55,777
9.00	25,128	12,213	67,989
10.00	28,042	26,585	94,574
11.00	30,685	29,364	123,938

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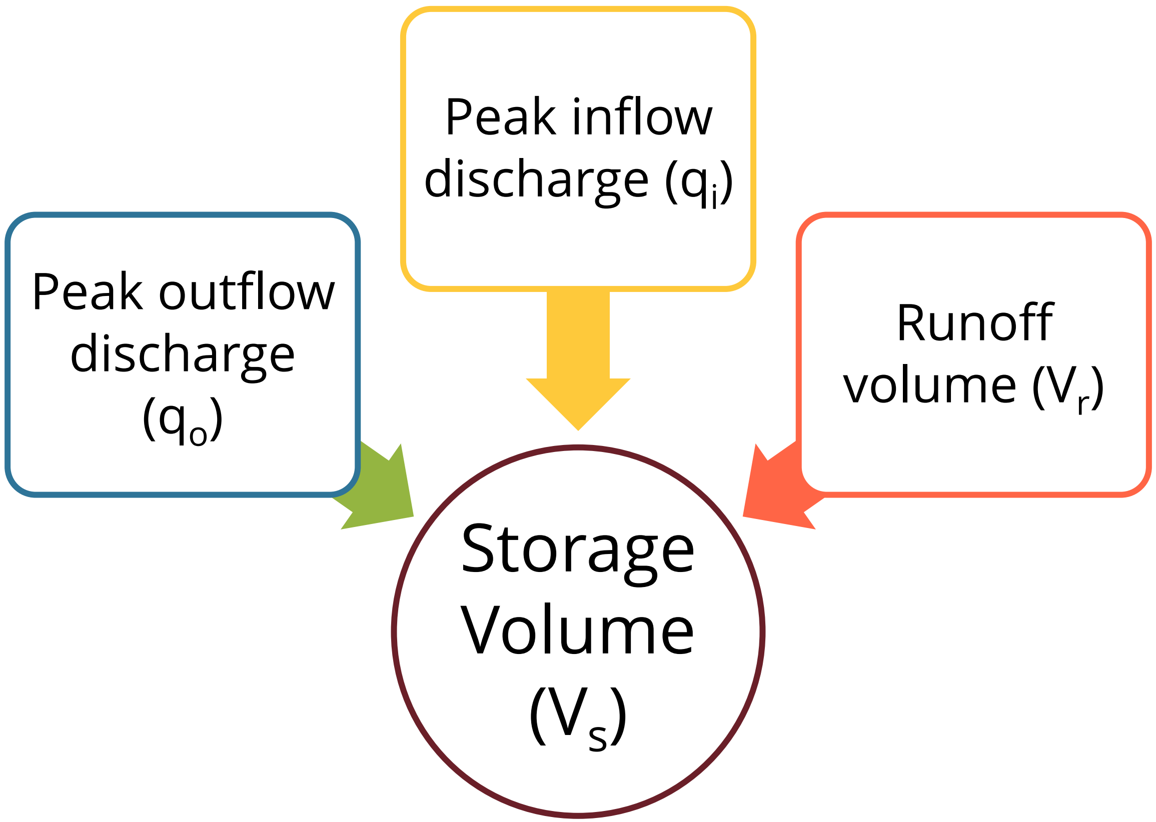
Storage Volume for Detention Basins TR-55 (Demonstration Purposes)

- Simplified procedure for estimating required storage volume (V_s)
- Suitable for estimating required storage for **preliminary design**
- **Not** suitable for final design

Storage Volume for Detention Basins

Information needed to estimate storage volume (V_s):



Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required
  1. Determine q_o
  2. Estimate q_i (chapters 4 or 5 of TR-55)

Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)

  3. Compute q_o/q_i and determine value for V_s/V_r from Figure 3-9 (pg 37)

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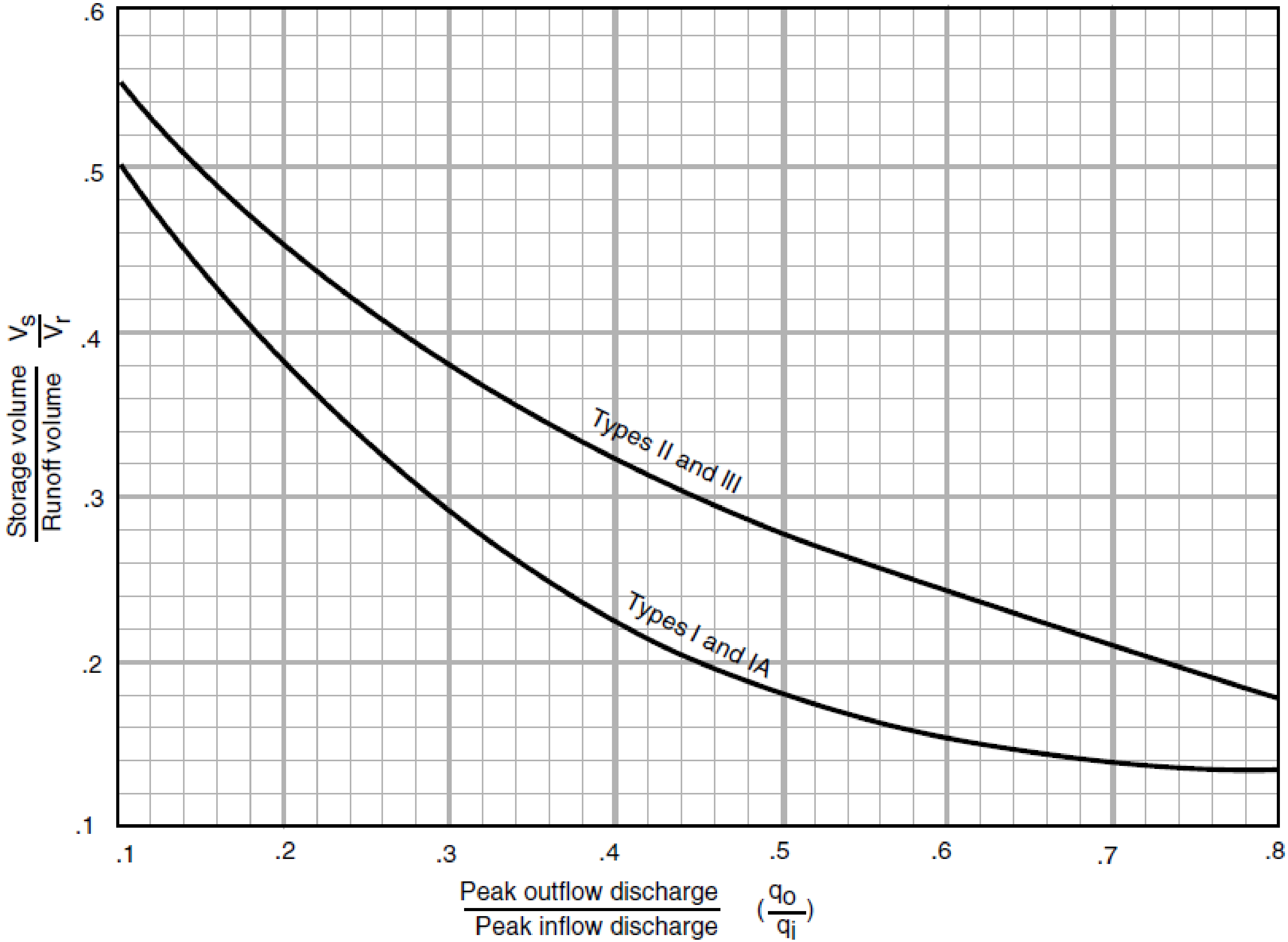
Figure 3-9 Approximate Detention Basin Routing



Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)

4. Q (in inches) was determined when computing q_i in step 2
   - Now convert to units in which V_s is to be expressed

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Storage Volume for Detention Basins

- Design procedure to estimate V_s storage volume required (cont.)

5. Use results of steps 3 and 4 to compute V_s

$$V_s = V_r \times \left(\frac{V_s}{V_r} \right)$$

V_r = runoff volume (acre-ft)

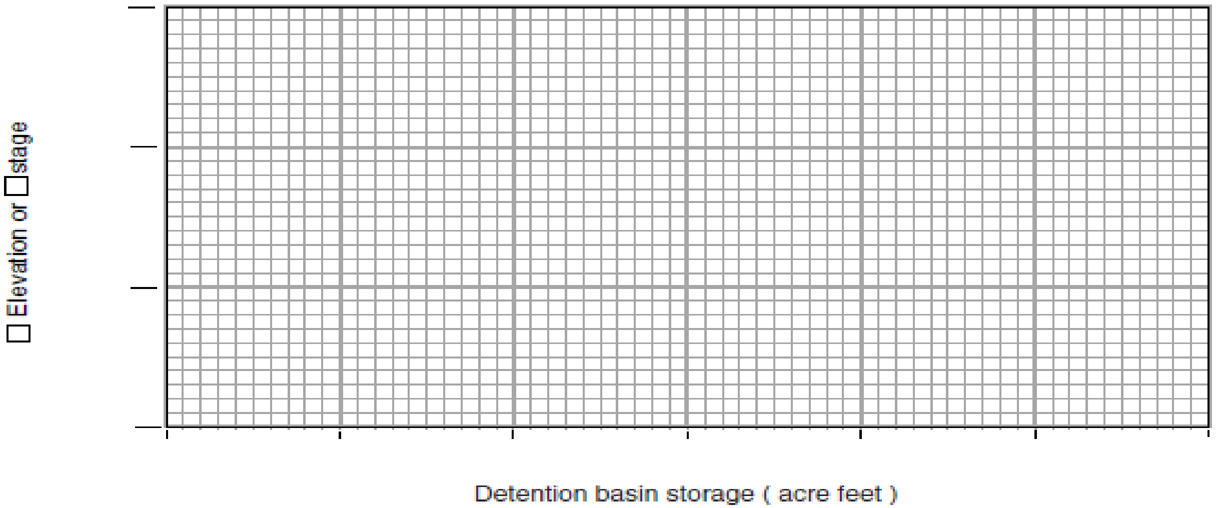
V_s = storage volume required (acre-ft)

(V_s/V_r) from Figure 3-9

Worksheet 6a: Detention basin storage, peak outflow discharge (q_o) known

Project	By	Date
Location	Checked	Date

Check one: ☐ Present ☐ Developed



1. Data:
   Drainage area .... A_m = __________ mi²
   Rainfall distribution type (I, IA, II, III) = __________

	1st Stage	2nd Stage
2. Frequency .... yr		
3. Peak inflow discharge q_i .... ft³/s (from worksheet 4 or 5b)		
4. Peak outflow discharge q_u .... ft³/s		1/
5. Compute $\frac{q_o}{q_i}$		
6. $\frac{V_s}{V_r}$ .... (Use $\frac{q_o}{q_i}$ with figure 6-1)		
7. Runoff, Q .... in (From worksheet 2)		
8. Runoff volume V_r.................. ac ft ($V_r = QA_m$ 53.33)		
9. Storage volume, V_s .... ac-ft ($V_s = V_r (\frac{V_s}{V_r})$)		
10. Maximum storage E_{max} (from plot)		

1/ 2nd stage q_o includes 1st stage q_o.

Worksheet 6a from TR-55 is useful for documenting inputs and results

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Example: Estimate Storage Volume

Given:

- 3-acre site in Richmond, Virginia (Type II)
- Developed discharge rate into the basin $= 10$ cfs $= q_i$
- Allowable discharge rate $= 2$ cfs $= q_o$
- Developed runoff volume = 1.33 inches

Example: Estimate Storage Volume

$$\frac{V_s}{V_r} = 0.45 \pm$$

$$\frac{q_o}{q_i} = \frac{2}{10} = 0.2$$

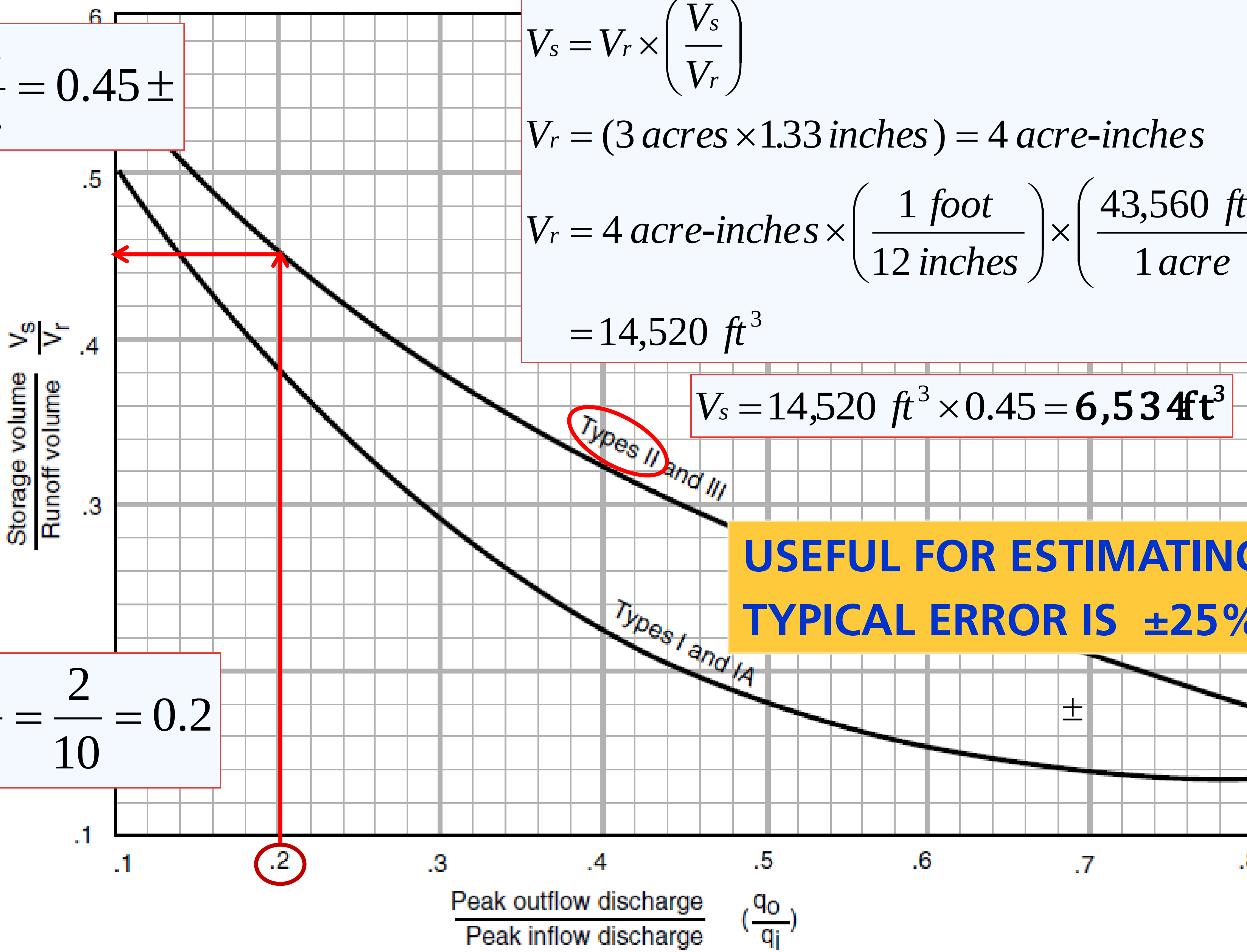
$$V_s = V_r \times \left(\frac{V_s}{V_r}\right)$$

$$V_r = (3\,acres \times 1.33\,inches) = 4\,acre\text{-}inches$$

$$V_r = 4\,acre\text{-}inches \times \left(\frac{1\ foot}{12\,inches}\right) \times \left(\frac{43{,}560\ ft^2}{1\,acre}\right)$$

$$= 14{,}520\ ft^3$$

$$V_s = 14{,}520\ ft^3 \times 0.45 = \mathbf{6{,}534\,ft^3}$$



USEFUL FOR ESTIMATING

TYPICAL ERROR IS ±25%

Design of hydraulic control structures

- Stormwater management facilities
- BMPs

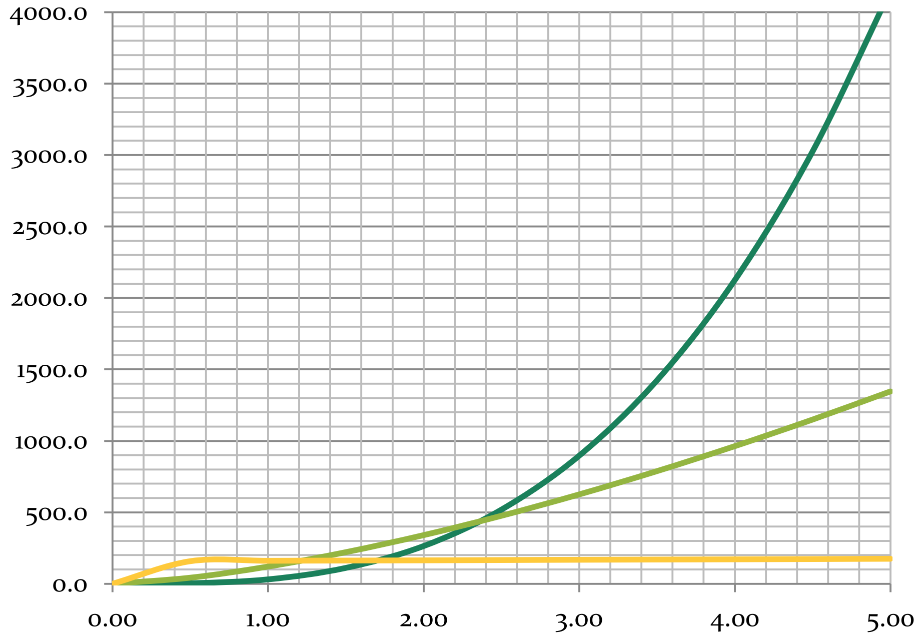
Discharge rating cures

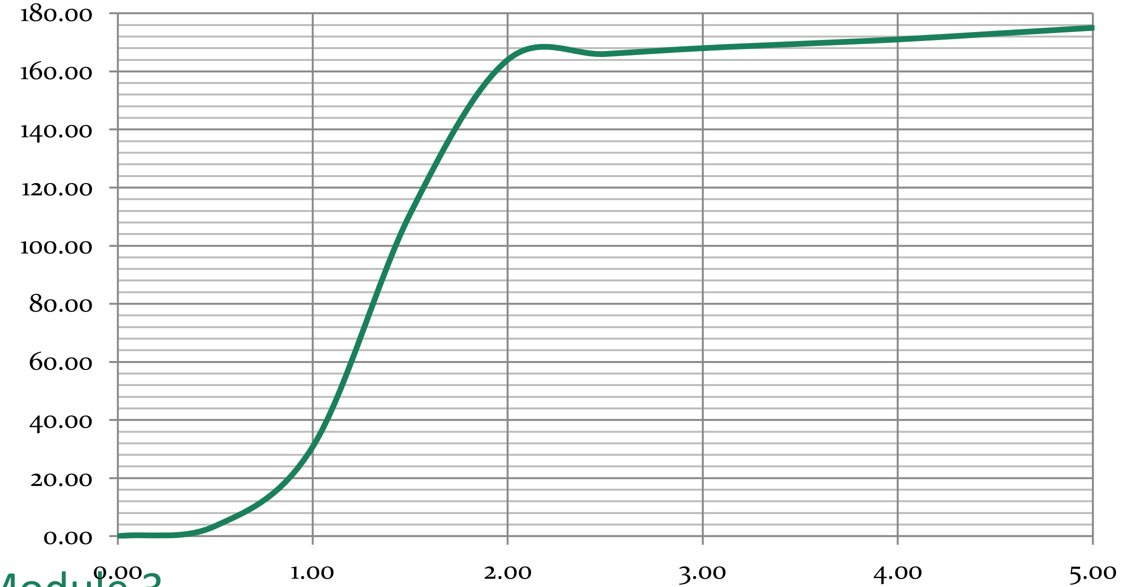
- Describe outflow discharge associated with elevation of upstream water

Three flow equations need to be evaluated

Weir
Orifice
Pipe

The equation that yields the smallest value controls


4000.0
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
0.00
1.00
2.00
3.00
4.00
5.00


180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00

Module 3

Hydraulic Control Design

Weir: A structure placed across a waterway to regulate or measure flow or discharge

$$Q_w = C_w \times L \times h^{1.5}$$

Q_w = Weir discharge (cfs)

C_w = Dimensionless weir coefficient

L = Length of weir (ft)

h = Hydraulic head (ft)

Hydraulic Control Design

An **orifice** is another type of structure used to control or measure discharge

$$Q = C \times a \times \sqrt{2 \times g \times h}$$

Q = orifice discharge (cfs)

C = dimensionless orifice coefficient*

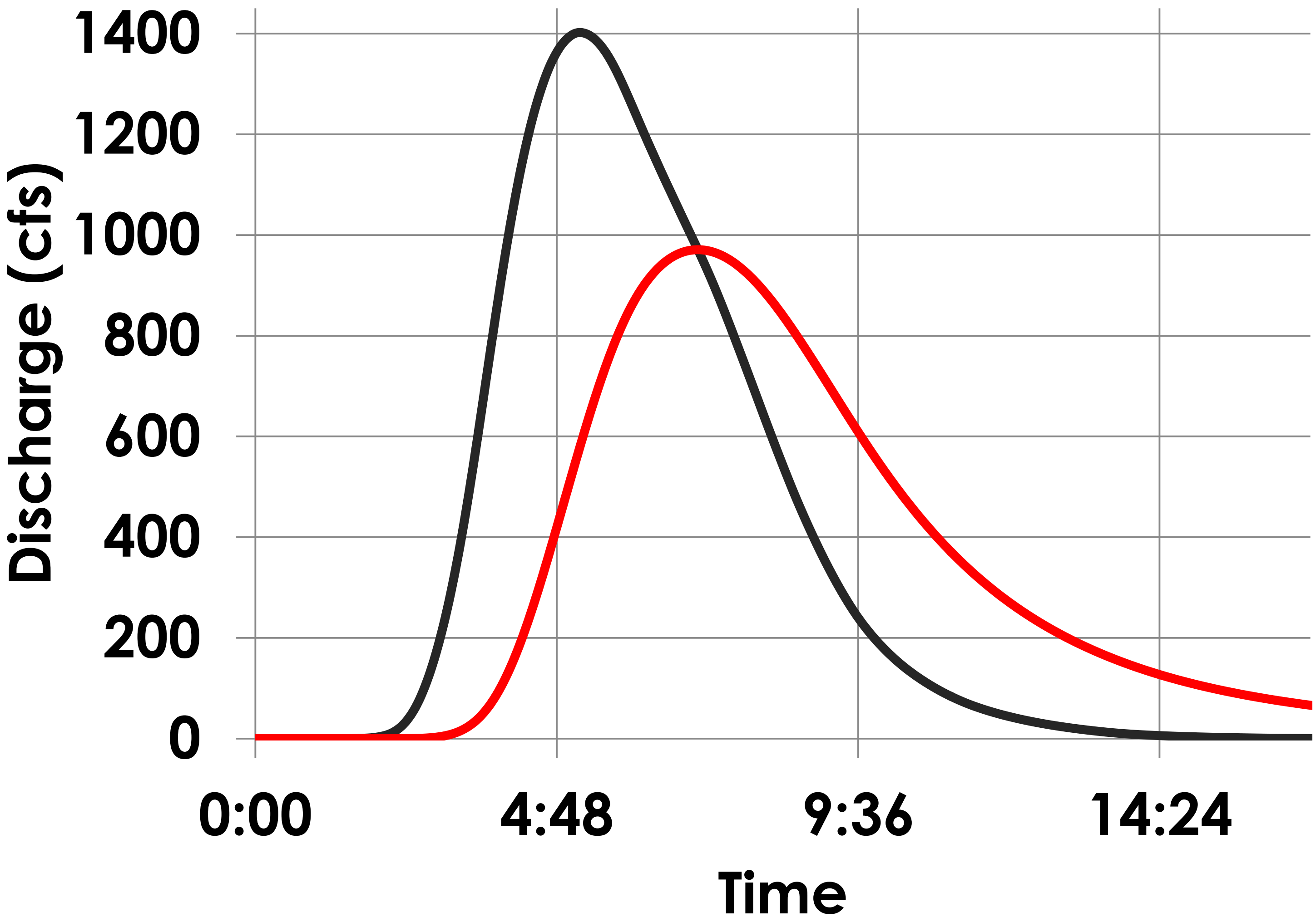
A = orifice area (ft^2)

G = gravitational acceleration (32.2 ft/sec^2)

h = hydraulic head (ft)

Pipe Equation

Results of Routing



Runoff Reduction Method

$$L = P \times Pj \times Rv \times C \times A \times {}^{2.72}\!/_{12}$$

Estimates annual pollutant load exported in stormwater runoff from small urban catchments

Runoff Reduction Method

$$L = P \times Pj \times Rv \times C \times A \times {}^{2.72}\!/_{12}$$

L (lbs/yr) = total post-dev. pollutant load

P (in) = average annual rainfall depth

= **43** in. (VA)

$\boldsymbol{P_j}$ = fraction of rainfall producing runoff

= 0.9

Runoff Reduction Method

$$L = P \times Pj \times Rv \times C \times A \times {}^{2.72}\!/_{12}$$

Rv **= volumetric runoff coefficient**

C (mg/L) = flow-weighted event mean concentration (EMC) of TP = 0.26

A (acres) = area of development site

Runoff Reduction Method

$$L = P \times Pj \times Rv_{composite} \times C \times A \times {}^{2.72}\!/_{12}$$

$Rv_{composite} =$ **Weighted runoff coefficient**

$$Rv_{composite} = (Rv_I \times \%I) + (Rv_T \times \%T) + (Rv_F \times \%F)$$

Rv_I = Runoff coefficient for Impervious cover (0.95)

Rv_T = Managed Turf/Disturbed soils

Rv_F = Forest/Open Space

Treatment Volume & BMP Sizing

$$Tv_{BMP} = \frac{(P \times Rv_{composite} \times A)}{12}$$

Tv_{BMP} = Treatment Volume from contributing drainage area to BMP + remaining runoff from upstream practices

P = 90th Percentile rainfall depth = 1”

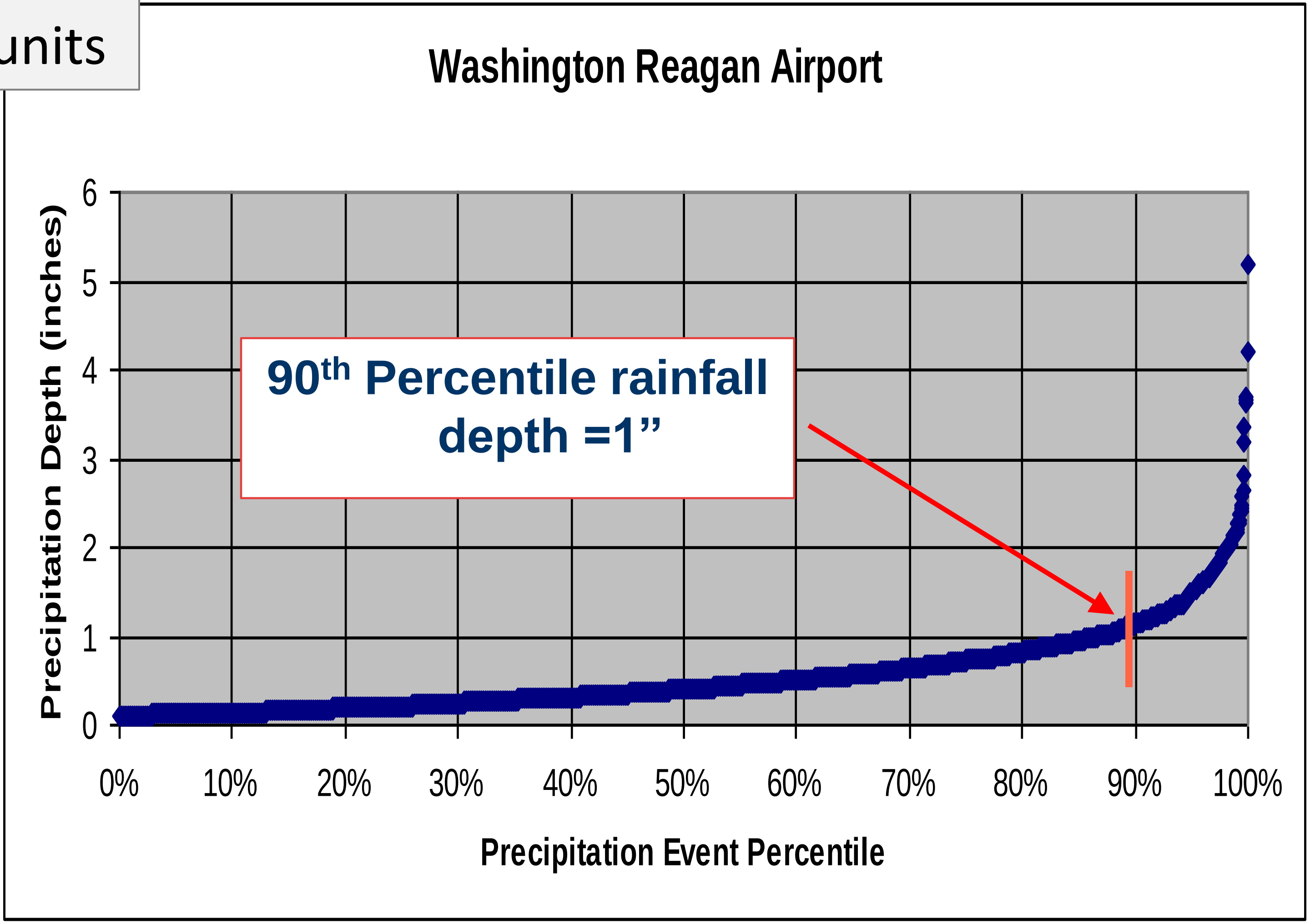
$\boldsymbol{Rv_{composite}}$ = **Weighted runoff coefficient**

A = Contributing drainage area to BMP

Design Rainfall - 90% Rule

Tv = P * Rv *A

Tv: volume units



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Water Quality Treatment Volume Peak Flow Rate

$$q_{pTv} = q_u \times A \times Q_a$$

q_{pTv} = Treatment Volume peak discharge (cfs)

q_u = unit peak discharge (cfs/mi^2/in

A = drainage area (mi^2)

Q_a = runoff volume (watershed inches), equal to Tv/A

***Volumetric conversion to an intensity - 1" in 24 hr. assumes NRCS type II rainfall distribution**

$q_p = q_u A_m Q F_p$

Initial Abstraction

TABLE 5-9

I_a VALUES FOR RUNOFF CURVE NUMBERS

Curve Number	I_a (inches)	Curve Number	I_a (inches)	Curve Number	I_a (inches)
40	3.000	60	1.333	80	0.500
41	2.878	61	1.279	81	0.469
42	2.762	62	1.226	82	0.439
43	2.651	63	1.175	83	0.410
44	2.545	64	1.125	84	0.381
45	2.444	65	1.077	85	0.353
46	2.348	66	1.030	86	0.326
47	2.255	67	0.985	87	0.299
48	2.167	68	0.941	88	0.273
49	2.082	69	0.899	89	0.247
50	2.000	70	0.857	90	0.222
51	1.922	71	0.817	91	0.198
52	1.846	72	0.778	92	0.174
53	1.774	73	0.740	93	0.151
54	1.704	74	0.703	94	0.128
55	1.636	75	0.667	95	0.105
56	1.571	76	0.632	96	0.083
57	1.509	77	0.597	97	0.062
58	1.448	78	0.564	98	0.041
59	1.390	79	0.532		

Water Quality Treatment Volume Peak Flow Rate

$$CN = \frac{1000}{\left[10 + 5P + 10Q_a - 10(Q_a^{2} + 1.25Q_aP)^{0.5}\right]}$$

CN = Curve Number

P = Rainfall (inches), 1.0” in Virginia

Q_a = Runoff volume (watershed inches), equal to Tv/drainage area

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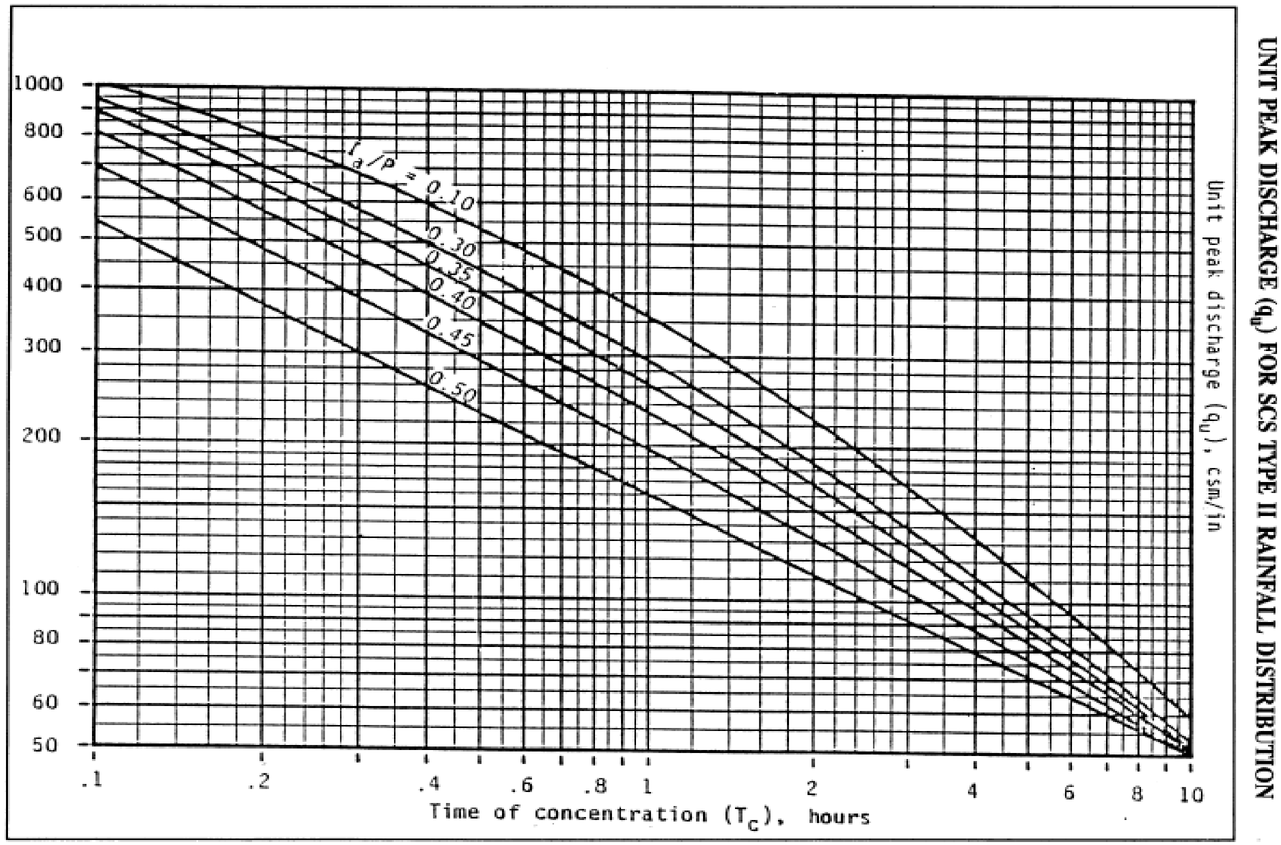
$q_p = q_u A Q$

Find q_u on chart (type II)

- Use I_a/P ratio and t_c value to find q_u
- For CN of 98 Ia/P=.041



Questions?